THERMAL ASPECTS IN GRINDING

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By
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to the

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CERTIFICATE

This is to certify that the work entitled ''THERMAL ASPECTS IN GRINDING'' by Anil Kumar Srivastava has been carried out under my supervision and has not been submitted elsewhere for a degree.

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A.K.Srivastava

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NOTATION

A	Wear flat area
A'	Average cross-sectional area of the chip
b	Width of the groove
b'	Mean chip width
c	Number of cutting-edges per unit area
D	Wheel diameter
d	Maximum depth of cut
F_R	Rubbing force
F_c	Cutting force
F_t	Total tangential force
GR	Grinding ratio
g	Mean diameter of abrasive grain
K	Thermal conductivity of work piece material
K'	Fraction of cutting energy entering the work piece
K'''	Fraction of grinding energy entering the work piece
k	Thermal diffusivity of work piece material
2ℓ	Heat source width
ℓ_c	Chip length
q	Heat source intensity (Cal/cm^{2}sec)
$q_{s/p}$	Average shear plane heat flux
q_s	Sliding heat source strength
q_I	Overall interference zone heat flux

r	Ratio of mean chip width and mean chip thickness
r_o	Initial grain tip radius
r_1	Radius of curvature of worn-surface
s	Screen number
T_{max_I}	Maximum interference zone temperature
T_{max_R}	Maximum sliding temperature
$T_{ave_{s/p}}$	Average shear plane temperature
$T_{max_{s/p}}$	Maximum shear plane temperature
t	Mean chip thickness
t_{max}	Maximum chip thickness
t_1	Undeformed chip thickness at any point along the shear plane
t_2	Shear plane heat source width
t_g	Grinding time
U	Specific energy of grinding
V	Wheel speed
V_1	Volume of abrasive wear
V_2	Volume of material removed
V'	Speed of moving heat source
v	Table speed
W	Vertical load on the wear flat
z'	Depth below the work piece surface

α	Radial grain wear
τ	Wheel-life
φ	Dimensionless wear parameter
$\emptyset$	Shear angle
γ	Distance from the beginning of chip
μ	Coefficient of friction
ε	Wear flat width

SYNOPSIS

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In grinding due to high cutting speeds and high friction conditions, the wheel work interface temperature is much higher than those encountered during conventional machining operations. This temperature has significant influence on grinding forces, wheel-wear and wheel-life. In the present work, an analytical approach has been used to correlate these three important parameters. The theoratical analysis shows how the cutting and rubbing forces vary with wear. For simplicity only attritious-wear of grains is considered and the grains have been assumed to be spherical in shape. The estimation of temperature-rise

on the work surface is based on Jaeger's moving heat source theory for a semi-infinite body subjected to an instantaneous moving heat source.

Theoratical results indicate that cutting force increases with increase in depth of cut, table speed and wheel diameter but decreases with increase in wheel speed. For a specified grinding condition the cutting force decreases continuously as grinding-progresses while the rubbing force increases. Similarly rubbing force increases with increase in table speed and depth of cut but decreases when wheel-speed and wheel diameter are increased.

The shear plane temperature does not appear to be significantly effected by wheel wear but it increases with increase in table speed, depth of cut and wheel diameter. The sliding temperature increases as the wear flat developes and also with increase in table speed, depth of cut and wheel speed. The overall interference zone temperature also increases with increase in depth of cut or wheel speed but decreases when table speed is increased. Thus work piece burn can be avoided by using higher table speeds. The wheel life, on the other hand, was found to decrease with increase in table speed. An optimum value of table speed should, therefore, be chosen to obtain maximum wheel-life without work-piece burn.

Comparison with available experimental results show qualitative agreement with the analytical results.

CHAPTER-1

INTRODUCTION AND PREVIOUS WORK

1.1 Introduction : -

Grinding is very similar to other metal cutting operations and can be described as a multi-tooth operation in which a number of abrasive grains held by a bonding material perform the cutting operation. In the past much less attention was devoted to the grinding process in comparison to other cutting processes due to inherent complexity of the process. In recent years, increasing interest in the mechanics of grinding has resulted in further understanding of the process. The grinding process is dependent on the inherent properties of the grinding wheel i.e. type of abrasive, size, distribution of grits and type of bond material.

In the grinding process, the cutting is performed by a large number of small abrasive grains of very hard material. Typical abrasives are aluminium oxide, silicon carbide and diamond. While both silicon carbide and aluminium oxide are hard enough to grind most engineering materials, silicon carbide is more suitable for grinding materials of low tensile strength and aluminium oxide is most efficient when applied to hard, tough materials.

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The size of grains used in a wheel is designated by a number corresponding to the number of openings per linear inch in the screen used to size the grain. The mean diameter of an abrasive grain (g) is approximately related to the screen number (s) by

$$sg = 0.7$$

The variation of average grain diameter with nominal grain size is shown in Fig. 1.1. These grits are held by a suitable bonding material, the amount of which decides the grade or hardness of the wheel indicating the relative strength of the holding matrix.

Wearing is an integral part of the process. It can be due to attrition, fracture and chemical action. Attritious wear is the gradual wearing away of the sharpness of the cutting points. Fracture occurs when the grits or the bond holding the grits are unable to sustain the grit forces. Often at high interface temperatures chemical reaction or diffusion may take place between the work piece and grits. The different types of wearing are shown in Fig. 1.2. A curve relating the volume of wheel wear with the volume of material removed is shown in Fig. 1.3.

The conventional idea regarding wheel wear is that as grains become dull, the force on them increases,

causing them to shatter or break out. This can not explain the wheel wear that takes place within ten seconds of grinding, since dulling requires around one minute to become appreciable. To explain this, the effect of temperature must be included. Wear volume is sensitive to the increasing temperature values. Under conditions of extreme normal pressure or very high temperature, accelerated wear may occur.

Thus the temperature plays an important role in the grinding operation. Also the grinding temperature has important effects upon the thermal damage of the ground surface and the size accuracy of the work piece. Such high temperatures may cause tempering, softening and sometimes thermal cracking of the work piece also. The bulk temperature rise of the work piece may lead to dimensional inaccuracies as well as concave surface for a plane due to uneven temperature distribution in the work piece. In order to understand and control these effects, it seems desirable to study the temperature distribution in the grinding.

1.2 Previous Work :-

The first attempt to evaluate the grinding chip temperature appears to have been made by Guest (1) in 1915. He assumed that just half of the total heat went into the

chips. The temperature calculated was surprisingly high. He concluded that if the horse power per unit volume is increased, the temperature of the grinding chips also increases, also harder the grade and finer the grain size, the higher is the temperature rise. In 1951, Mckee and others (2) measured the average surface temperature during cylindrical grinding of hardened steels using the thermocouple method and observed a temperature rise of $5^{o}C$ to $30^{o}C$ during grinding with various coolants.

In 1952, Shaw and others (3) presented a theoratical analysis for evaluating grinding temperature using the theory of moving heat source originated by Jaeger (4) under the assumption that the cutting edge of the grit was a minute bit having a rake angle of zero degree. An example of calculated temperature gave $2125^{o}F$ for fine surface grinding. They also measured the grinding temperature by means of the thermo-electromotive force between the steel work piece and the silicon carbide grit. Their results are shown in Fig. 1.4. In this case, the grinding temperature increased with the increase in table speed. The measured temperature was some average temperature of all places of contact between the rake faces of the grains and chips during cutting and between the clearance faces of the grains and the work piece surface.

In further experiments,Shaw and Mayer (5) used a photoconducting lead sulfide cell to sight radiating surface of the ground work piece through a hole in the grinding wheel. Their calculated shear plane temperatures were,however, three to five times the measured temperatures.

Sato (6) in 1957, estimated the heat generated during grinding from the tangential grinding forces. He analytically found the ratios of heat entering the work, the chips and the wheel. He also determined the temperature at the work wheel contact surface from the heat quantity conducted to the work piece. His theory was based on the temperature rise of the surface of a semi-infinite body under an instantaneous heat source. The effects of grinding variables upon the grinding temperatures were also explained. Lastly, he verified the theoratical analysis by the measurements of grinding temperatures using the grit work thermocouple method. Sato (6) revealed that about 85 % of the grinding energy is conducted as heat into the work piece.

Littman (7) used thermocouple embedded beneath the work piece surface to measure temperatures at various depths as material was removed from the work piece surface in successive grinding passes. He did not correlate experimental temperatures with theoratically calculated

temperatures. The effect of measured temperatures on hardness changes of the work piece material was discussed.

Hahn (8) discussed the effect of grinding conditions on temperature. Des Ruisseaux and Zerkle (9) used the concepts of both a local and an average grinding temperature in order to calculate the surface temperature distribution in grinding. It was reasoned that the temperature distribution in the vicinity of an abrasive grain is due not only to the grinding action of an individual grain, but due to the grinding action of all other grains in the grinding zone. The grinding temperature then can be calculated as the sum of a local temperature due to grinding by an individual grain, and a grinding zone temperature due to grinding by all other grains. He considered the temperature distribution as a function of depth into the work piece and showed that temperatures on the surface of material which remains after grinding do not necessarily reach magnitudes corresponding to chip shear plane temperature. Furthermore, the temperature in the work piece at a distance slightly below the surface (below 4μ) are virtually unaffected by chip shear plane temperature.

Malkin and Anderson (10) discussed the energy partition among chip formation, ploughing and sliding energy components, and the portions of each of these energies

which are conducted as heat to the work piece. He concluded that virtually all the sliding and ploughing energies, and approximately 55 o/o of the chip formation energy, are conducted as heat to the work piece. Lastly, he related these results to the grinding temperatures, Fig. 1.5, and work piece burn.

Scrutton and Lal (11) presented a thermal analysis of a single abrasive grain and then related the temperature in the vicinity of the grain with the wear of a single abrasive grain. They assumed that the rise in temperature at the grain-work piece interface decreases the shear flow stress of the softer material which permits a greater adhesive wear rate. They assumed that energy expended during grinding enters the work piece via adiabatic plastic flow. Their theoratical results agreed with the extensive experimental results.

1.3 Present Work :-

In grinding due to high cutting speed, which means plastic deformation at high strain-rate, and high friction at the grain-work interface arising out of high cutting speed as well as irregular geometry of the grits, the wheel work interface temperature is much higher than in any other metal cutting process. Temperature is one of the major factors which influence grinding forces

and wear. Wear increases the forces and the force, on the other hand is a major cause of temperature rise. Thus these three parameters are interdependent and no attempt has been made in the past to correlate these three important parameters. In the present work, an analytical approach has been used to estimate the cutting and rubbing forces with increasing wear and to correlate these forces with grinding temperatures. The theory is based on simple attritious wear mechanism of a single abrasive grain which has been assumed spherical in shape. The estimation of temperature rise on work piece surface and at the grain tip is based on the Jaeger's (4) moving heat source theory for a semi-infinite body subjected to an instantaneous moving heat source. The effects of grinding variables upon the grinding temperature are discussed and an attempt has been made to relate the wheel life with grinding - temperature and forces. The effect of grinding variables upon wheel life is also discussed.

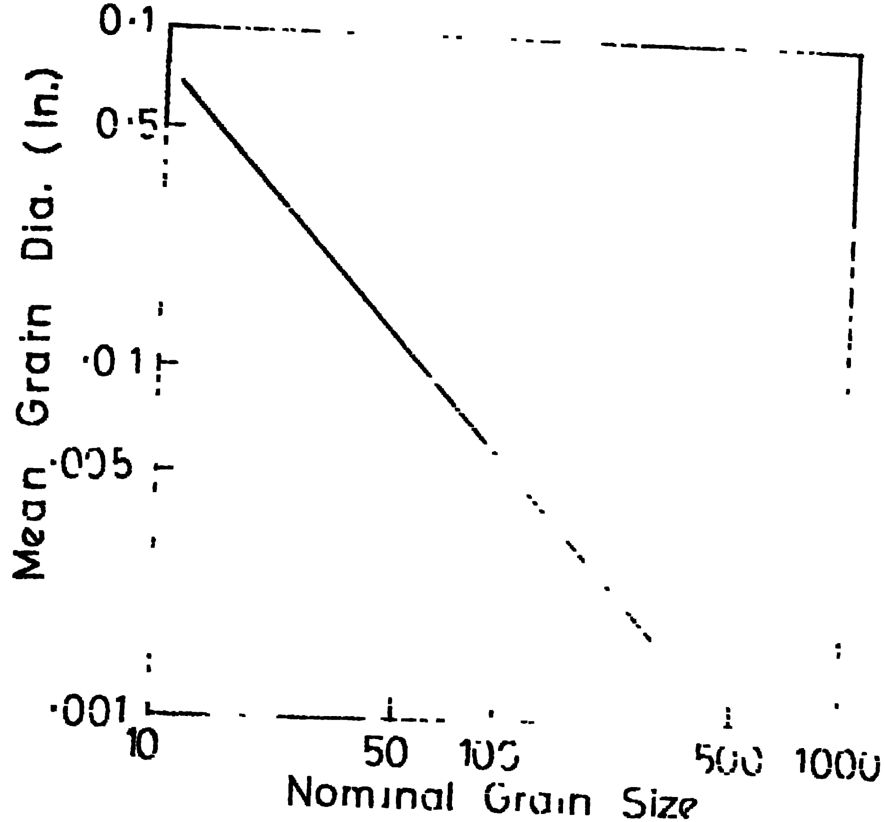


Fig. 1·1 GRAIN DIAMETER vs NOMINAL GRAIN SIZE.

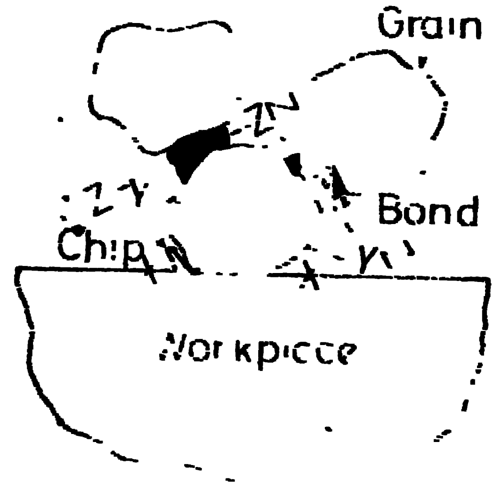


Fig 1·2 ILLUSTRATION OF THREE TYPES OF WEAR: X- ATTRITIOUS WEAR, Y- GRAIN FRACTURE, Z- BOND FRACTURE.

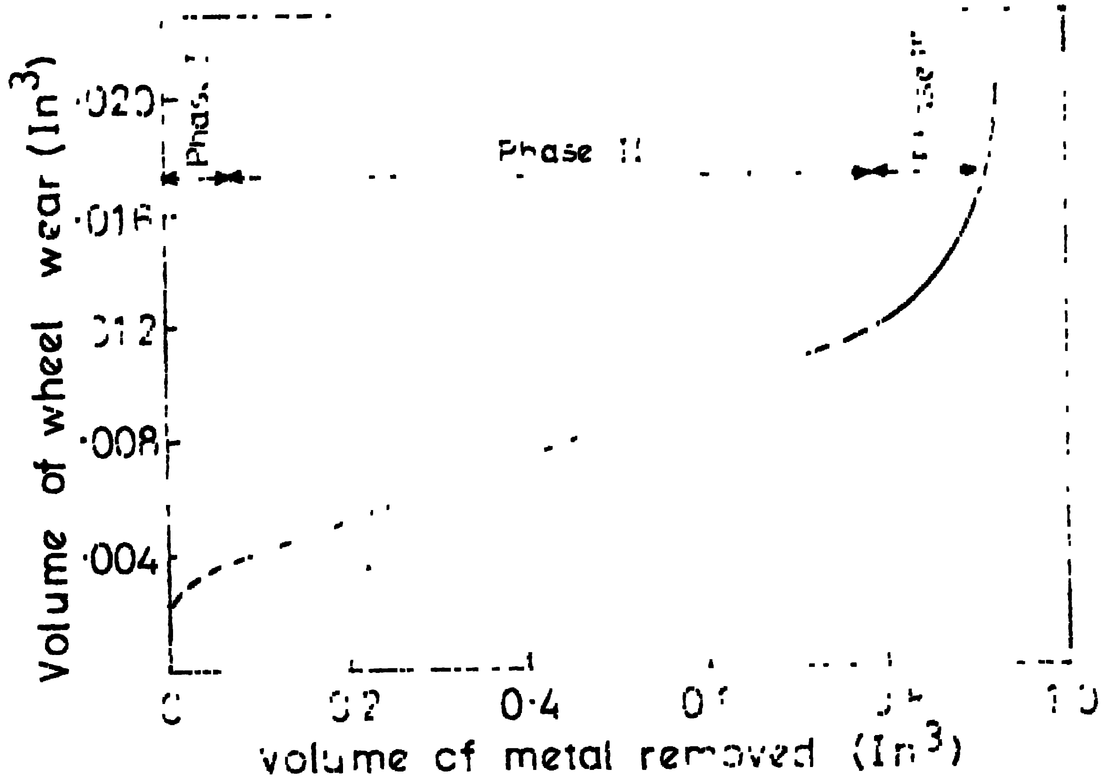


Fig 1·3 GRINDING WHEEL WEAR AS A FUNCTION OF VOLUME OF MATERIAL REMOVED.
[After Krabacher (17)]

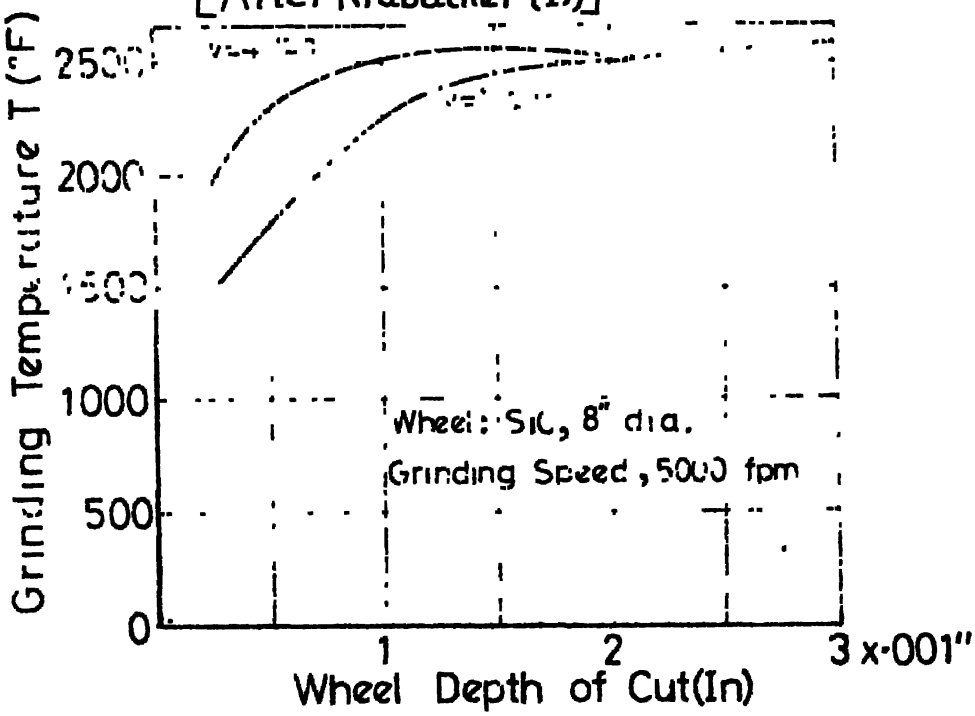


Fig. 1·4 EFFECT OF WHEEL DEPTH OF CUT ON GRINDING TEMPERATURE.
[After Outwater & Shaw (3)]

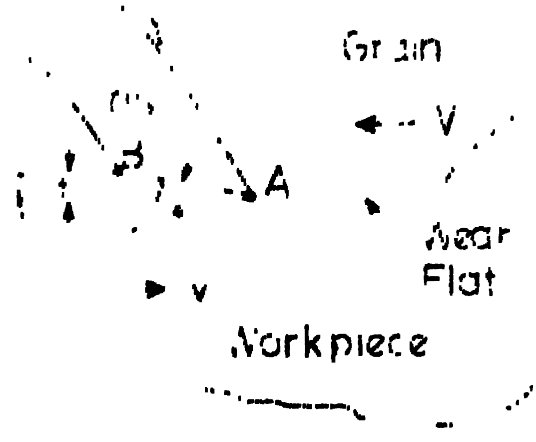


Fig.1·5 (a) ILLUSTRATION OF CHIP FORMATION AHEAD OF THE GRAIN AND SLIDING AT THE INTERFACE.

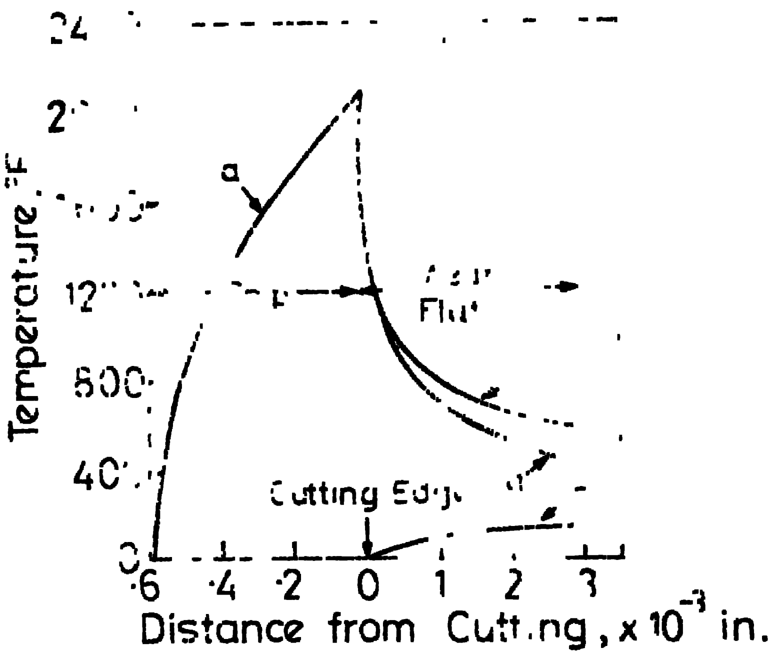


Fig.1·5 (b) TEMPERATURE DISTRIBUTION IN THE VICINITY OF AN ABRASIVE GRAIN DUE TO CHIP FORMATION SLIDING.

Curve (a) Represents temperature rise due to Chip format

Curve (b) Represents temperature rise due to sliding between the Wear flat and Work-piece.

Curve (c) Is the superposition of the Chip-formation and sliding temperatures.

[After MALKIN (10)]

CHAPTER - II

WHEEL-WEAR AND FORCES

2.1 Wheel-Wear :

An individual grain on the grinding wheel is generally assumed to be spherical in shape (11). Initially there is no wear flat area but as grinding proceeds, this progressively increases to M_2N_2, M_1N_1, MN and finally it may reach the complete grain depth of cut as shown in Fig. 2.1. Therefore as the wearing proceeds the effective depth of cut goes on decreasing and the radius of curvature of the worn-surface increases, but the maximum width of groove essentially remains constant.

Assuming the surface after wearing to be parabolic in shape, a general equation of the form

$$y^2 = 4a\,(x + x') \qquad (1)$$

can be used.

This parabola always passes through $(\alpha, 0)$ and $(dx, \sqrt{2r_o dx - dx^2})$, therefore

$$x' = -\alpha$$

and $a = \dfrac{(2r_o dx - dx^2)}{4(dx-\alpha)}$

and equation (1) reduces to

$$y^2 = \frac{(2r_o dx - dx^2)}{(dx - \alpha)}\,(x - \alpha) \qquad (2)$$

Here r_o is the initial grain tip radius and α is the radial grain-wear.

The radius of curvature (r_1) at any point is given by

$$r_1 = \frac{(1 + y'^2)^{3/2}}{\bar{y}''} \qquad (3)$$

Since $y^2 = 4a(x - \alpha)$, therefore

$$y' = \frac{2a}{y}$$

and $$y'' = -\frac{4a^2}{y^3}.$$

Substituting in equation (3) and neglecting higher order terms, we get

$$r_1 = \frac{(2r_o - dx)dx}{2(dx - \alpha)} \qquad (4)$$

Similarly the contact length ε can be evaluated from

$$\varepsilon = 2 \int_o^y (1 + y'^2)^{\frac{1}{2}} dx \qquad (5)$$

Again using equation (1) and neglecting higher - order terms, we get

$$\varepsilon \approx 2\sqrt{2r_o dx - dx^2} \qquad (6)$$

The maximum chip thickness (t_{max}) during surface grinding is given by (12)

$$t_{max} = \left(\frac{4v}{Vcr}\sqrt{\frac{d}{D}}\right)^{\frac{1}{2}} \qquad (7)$$

where V is the wheel speed, v is the table-speed, D is the wheel diameter, d is the depth of cut, c is the number of cutting points per unit area on the wheel surface and r is the ratio of mean chip width (b') and mean chip thickness (t) as shown in Fig. 2.2.

To an excellent approximation

$$t \approx \frac{1}{2}\, t_{max}$$

therefore,

$$t \approx \left(\frac{v}{Vcr}\sqrt{\frac{d}{D}}\right)^{\frac{1}{2}} \qquad (8)$$

As the grain wears out, the ratio r also varies. Therefore, from Fig.2.2.

$$r = \frac{b'}{t} = 2\sqrt{\frac{r_1}{t}} \qquad (9)$$

and

$$t = \left(\frac{v}{2Vc}\sqrt{\frac{t}{r_1}}\sqrt{\frac{d-\alpha}{D}}\right)^{\frac{1}{2}}$$

Or

$$t = \left(\frac{v}{2Vc}\sqrt{\frac{d(1-\varphi)}{r_1 D}}\right)^{2/3} \qquad (10)$$

where $\varphi = \frac{\alpha}{d}$.

The wear flat area (A) at any instance of wearing (Fig.2.3) will be

$$A = 2\pi \int y\, ds = 2\pi \int y \sqrt{1 + \left(\frac{dx}{dy}\right)^2}\, dy \qquad (11)$$

Using equation (1) and integrating, we get

$$A \approx \pi\, dx\, (2r_o - dx) \qquad (12)$$

It has been seen that during grinding, the width of the groove, b, essentially remains constant. Takenaka (13) and also Lal and Shaw (14) examined the geometry of worn single grains and found that the width of the groove is little influenced by the degree of wear of the abrasive grain. Therefore b can be assumed to remain constant. Thus at any instant

$$b^2 \simeq 8r_1 \cdot (d-\alpha) = 8r_o \cdot d \qquad (13)$$

Or
$$r_1 = \frac{r_o d}{d-\alpha} = \frac{r_o}{(1-\varphi)} \qquad (14)$$

Equating equations (4) and (14), we get

$$r_1 = \frac{2r_o dx - dx^2}{2(dx-\alpha)} = \frac{r_o}{(1-\varphi)} \qquad (15)$$

and finally

$$dx = r_o\left[\frac{\sqrt{\varphi^2 + 2d/r_o \cdot \varphi(1-\varphi)} - \varphi}{(1-\varphi)}\right] \qquad (16)$$

Substituting equation (14) in (10) we get

$$t = \left(\frac{v}{2Vc}\sqrt{\frac{d}{r_o D}}\right)^{2/3} (1-\varphi)^{2/3} \qquad (17)$$

Substituting for dx from equation (16) into equation (12), gives

$$A \approx 2\pi r_o^2 \left[\frac{\sqrt{\varphi^2 + 2d/r_o \cdot \varphi(1-\varphi) + d/r_o \varphi^2} - (1 + d/r_o) \cdot \varphi}{(1-\varphi)^2}\right]$$

(18)

As the grinding operation proceeds, the volume of abrasive wear also increases. The volume worn (V_1) can also be estimated as the function of φ in the following manner :

The abrasive volume worn away at any instant (Fig.2.4) will be

$$V_1 = \left[\int_0^{dx} \pi y^2 \, dx \right]_{spherical} - \left[\int_{\alpha}^{dx} \pi y^2 \, dx \right]_{paraboloid} \quad (19)$$

Using equation (1) and integrating, we finally get

$$V_1 = \frac{\pi}{6} dx \left[dx^2 + 6\alpha r_o - 3\alpha dx \right]$$

Or

$$V_1 = \frac{\pi}{6} d^3 \left[\eta^3 + 6p\eta\varphi - 3\eta^2\varphi \right] \quad (20)$$

where $\eta = \frac{dx}{d}$ and $p = \frac{r_o}{d}$.

The volume of work material removed at any instantaneous value of φ will be (Fig.2.5)

$$V_2 = \frac{2}{3} b \, dl_c \quad (21)$$

where l_c is the chip length = $\sqrt{dD}$. Substituting for l_c and solving, we get

$$V_2 = \frac{4}{3} \sqrt{2pS} \; d^3 \, (1-\varphi)^{3/2} \quad (22)$$

where $S = \frac{D}{d}$.

The grinding ratio (GR) is generally defined as the volume ratio of metal removed to wheel wear. Since the wearing of abrasive grains also reduces the volume of metal removed, the grinding ratio at a particular value of φ will be

$$GR = \frac{-dV_2/d\varphi}{dV_1/d\varphi} \tag{23}$$

where $dV_2/d\varphi$ is the rate of metal volume removed and $dV_1/d\varphi$ is the rate of abrasive wheel wear at a particular value of φ.

Using equations (20) and (22), we get

$$\frac{dV_2}{d\varphi} = -2\sqrt{2pS}\; d^3 (1-\varphi)^{\frac{1}{2}} \tag{24}$$

and

$$\frac{dV_1}{d\varphi} = \frac{\pi}{6} d^3 \left[(3\eta^2 + 6p\varphi - 6\eta\varphi)\eta' + 6p\eta - 3\eta^2 \right] \tag{25}$$

where

$$\eta' = \frac{\eta^2 + 2p - 2p\eta}{2\eta(1-\varphi) + 2p\varphi} \tag{26}$$

Using above equations, we get

$$GR = \frac{4\sqrt{2pS}}{\pi} \left[\frac{[2\eta(1-\varphi)+2p\varphi]\,(1-\varphi)^{\frac{1}{2}}}{\eta^4 - 2\eta^3(1+p) + 4p\varphi(p-\eta) + 6p\eta^2} \right] \tag{27}$$

2.2 Grinding-Forces :

When a grain comes in contact with the work piece wearing occurs due to rubbing, cutting, ploughing and very high temperatures in the vicinity of the grain. With wearing the wear flat area increases which was initially zero. With increasing wear flat area, the rubbing force increases rapidly until the fracture in the grain or bond occurs. The rubbing force, component F_R (Fig.2.6) can be given as

$$F_R = \mu W = \mu K_1 A F_V = \mu K_1 A K_2 F_H = \mu K_1 K_2 U A A' \qquad (28)$$

where A is the wear flat area, A' is the average cross sectional area of the chip ($\approx \frac{2}{3} b' t$), K_1 is the proportionality constant which will be a function primarily of detailed geometry at the grain tip, K_2 is a constant (very nearly two for a wide range of operating conditions), μ is the coefficient of friction (assumed constant), W is the vertical load on the wear flat and U is the specific energy (energy required to remove a unit volume of material).

Substituting for A from equation (12), the rubbing force becomes

$$F_R = \frac{4\pi}{3} \mu K_1 K_2 U_o d x(2r_o - dx) \sqrt{r_1 t} \qquad (29)$$

since $U \gtrsim \frac{U_o}{t}$ for fine-grinding (12), where U_o is a constant. Using equations (16), (17) and (29) and simplifying, we get

$$F_R = K_{Rf} \left[\frac{\sqrt{\varphi^2 + 2d/r_o \varphi(1-\varphi) + d/r_o \cdot \varphi^2} - (1+d/r_o)\varphi}{(1-\varphi)^{13/6}} \right] \tag{30}$$

where

$$K_{Rf} = \frac{8\pi}{3} \mu K_1 K_2 \mu U_o r_o^2 \left(\frac{vr_o}{2Vc} \sqrt{\frac{d}{D}} \right)^{1/3} \tag{31}$$

Equation (30) can be approximately written as

$$F_R = K_{Rf} \left[\frac{2(r_o-d) \cdot d \cdot \varphi(1-\varphi)^{-1/6}}{r_o(2\varphi(r_o-d)+d)} \right] \tag{32}$$

The cutting force (F_c) during grinding can be estimated from

$$F_c = \frac{2}{3} U \frac{v}{V} bd \tag{33}$$

Since $U \gtrsim \frac{U_o}{t}$, where U_o is a constant, using this and substituting for b and t from equations (13) and (17), respectively, we get

$$F_c = K_{Cf} (1-\varphi)^{1/3} \tag{34}$$

where $K_{Cf} = \frac{4\sqrt{2}}{3} U_o r_o^{5/6} \cdot d^{7/6} \left(2c \sqrt{\frac{vD}{V}}\right)^{2/3}$ (35)

In the dimensionless form this can be written as

$$\frac{F_c}{K_{Cf}} = (1-\varphi)^{1/3} \tag{36}$$

Therefore, the total tangential force acting at any time is

$$F_t = K_{Rf}\left[\frac{2(r_o - d).d.\varphi(1-\varphi)^{-1/6}}{r_o(2\varphi(r_o - d) + d)}\right] + K_{cf}(1-\varphi)^{1/3}$$

Or

$$F_t = K_{Cf}\left[\frac{(1-\varphi)^{1/2} + K_t\left[\frac{2(r_o-d).d.\varphi}{r_o(2\varphi(r_o-d)+d)}\right]}{(1-\varphi)^{1/6}}\right] \tag{37}$$

where

$$K_t = \frac{\pi K_1 K_2 \mu r_o^{3/2}}{\sqrt{2}\, d\, c\, D^{\frac{1}{2}}} \tag{38}$$

The total force during grinding can therefore be evaluated provided K_t is a known quantity. The value of K_t can be evaluated using the conditions.

$$\frac{dF_t}{d\varphi} = 0$$

and $$\frac{d^2F_t}{d\varphi^2} = 0$$ at the inflection point of the force.

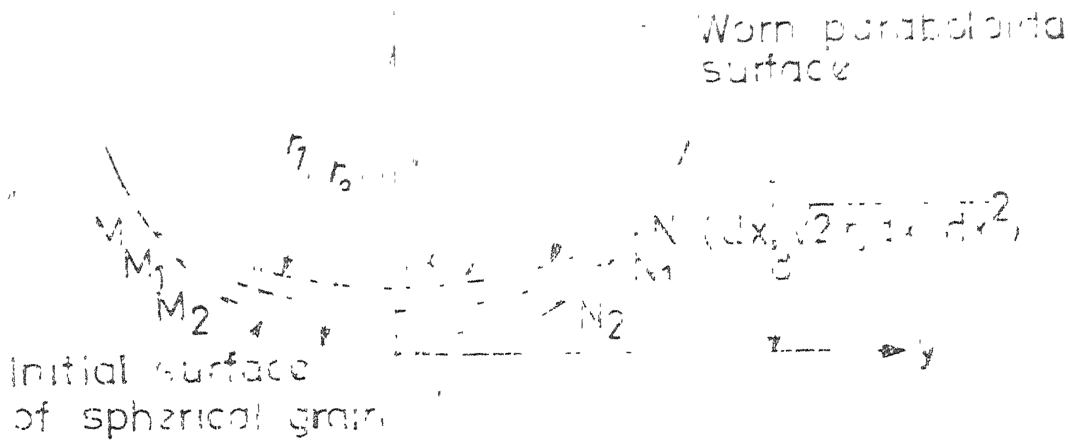


Fig. 2·1 GRAIN SHAPE BEFORE AND AFTER WEARING.

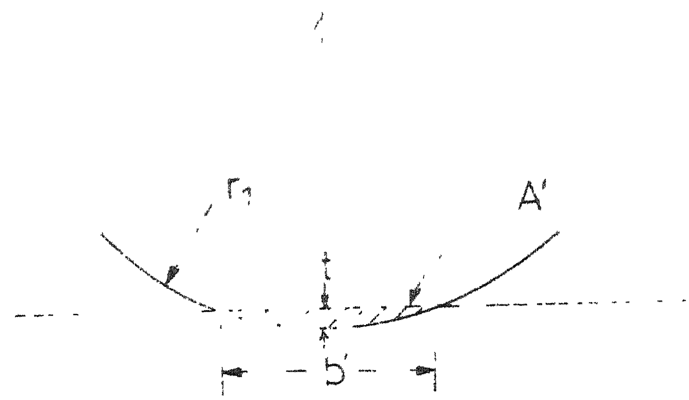


Fig. 2·2 TRANSVERSE AREA OF UNDEFORMED CHIP AT MID-POINT OF CUT.

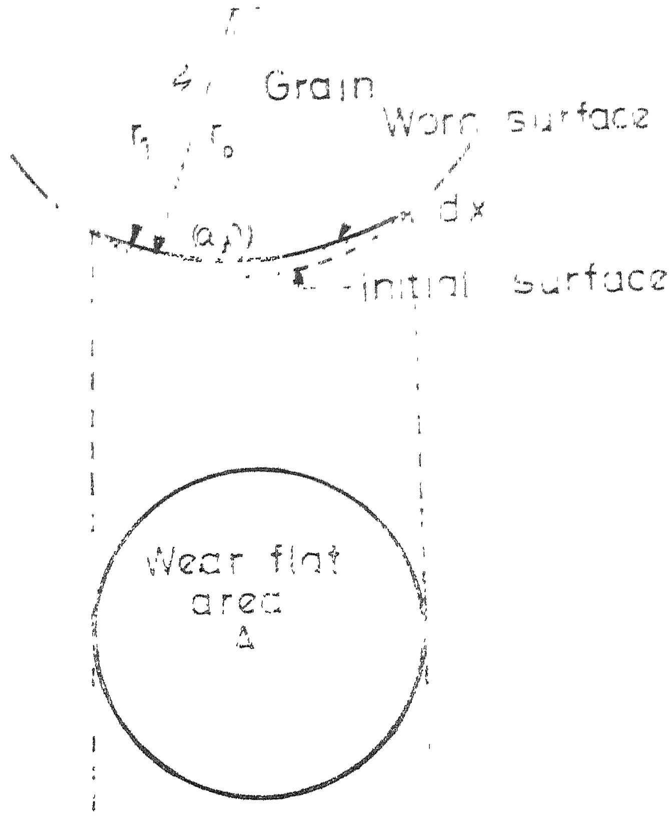


Fig 2·3 ABRASIVE GRAIN WITH WEAR FLAT AREA (A).

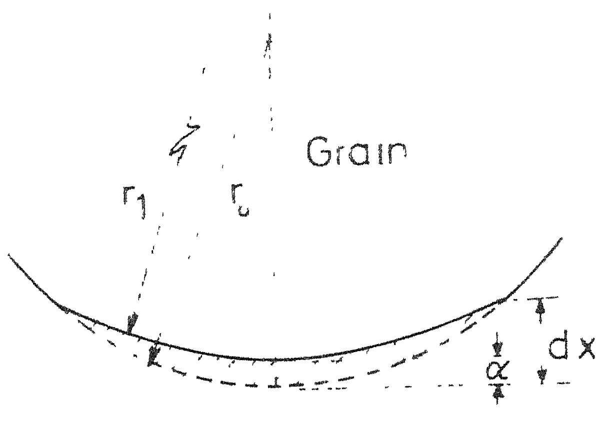


Fig. 2·4 WEAR VOLUME

Fig.2·5 WORK MATERIAL REMOVED AT ANY INSTANTANEOUS VALUE OF ϱ.

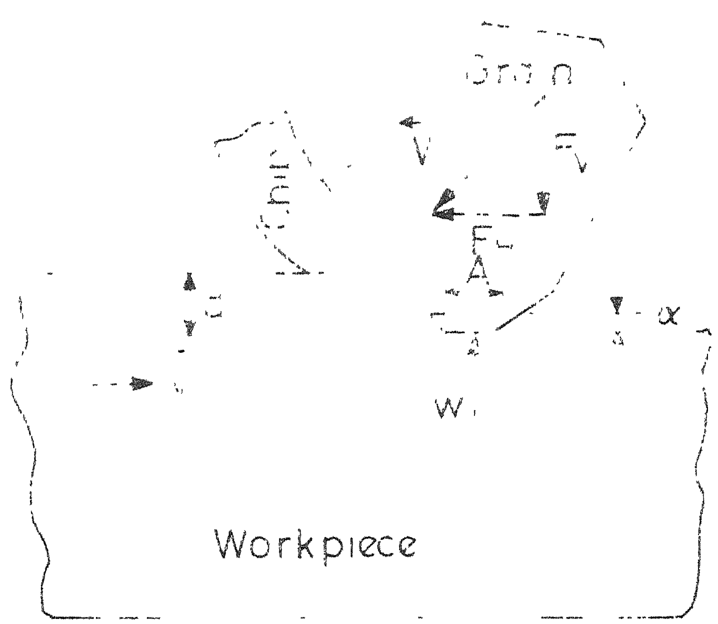


Fig 2·6 ABRASIVE GRAIN WITH WEAR LAND AREA A.

CHAPTER-III

THERMAL ANALYSIS

3.1 Grinding-Temperatures :

Fig.3.1, depicts, in an idealized manner, the chip formation in surface grinding. At the beginning of the interference zone, where the grain on the wheel first contacts the work-piece surface, sliding and ploughing occurs. At this location, forces are not sufficiently large to remove material. As the grain moves along the work piece, it encounters a thicker layer of uncut material, forces increase and a chip is removed. At every location of the grain on the work-piece,heat is generated at the interface due to frictional sliding. There is also heat generated in material which is being plastically deformed. Severe plastic deformation occurs in the region ahead of the grain where a chip is being removed. As the chip travels up the rake (leading) face of the grain, heat is generated between the chip and the grain. Thus, temperatures of large magnitude can occur in the vicinity of cutting edges. It is seen from Fig.3.1 that these temperatures occur on the surface of material which is removed during grinding. In addition to the temperature in the region of chip formation, the finished work-surface is also subjected to a wheel work-piece

interference zone temperature. The present work relates, for the first time, temperatures in the region of chip formation and overall interference zone temperature, to the temperature of the work-piece surface which remains after grinding. It is assumed that the chip formation occurs in a thin shear zone as in the case of conventional single point machining.

A major limitation in precision grinding of steels is work-piece burn. At the onset of work-piece burn, the grinding force and rate of wheel wear increase sharply and the surface quality deteriorates. For grinding of various steels, burning has been found to occur (15) when a critical wear flat area is reached, the magnitude of which depends upon the operating conditions and the particular steel being ground. Before continuing to grind, it is necessary to redress the wheel. In this way, work-piece burn can determine the wheel life. Therefore, the grinding conditions under which work-piece burn will occur, are of practical significance. The present work includes this important factor also.

Thermal analysis, to calculate these temperatures, is based on the Jaeger's moving heat source theory (4) on a semi-infinite body. The model adopted is shown in Fig.3.2. It consists of a continuously acting uniform band heat

source on the surface of a moving semi-infinite body. The co-ordinate axes are fixed to the centre of heat source, which is of width 2ℓ. There is assumed to be no heat loss from the surface of the semi-infinite body. The two dimensional, steady state temperature distribution (T) is determined as

$$T = \frac{2kq}{\pi KV'} \int_{X-L}^{X+L} e^{-u} K_o \left[Z^2+u^2\right]^{\frac{1}{2}} du \qquad (39)$$

where

$$X = \frac{V'x'}{2k}, \quad Z = \frac{V'z'}{2k} \text{ and } L = \frac{V'\ell}{2k}$$

Here k is the thermal diffusivity of the work material, K is the thermal conducting of the work-piece material, q is the heat source intensity, z'is the depth below the work surface and V' is the speed of the moving heat source.

The temperature distribution given by the above equation is the rise above ambient, and can be evaluated from table given in reference (4). Two useful approximations are

$$T_{max} = \frac{4kq}{\pi KV'} \sqrt{\pi L} \qquad \text{for } Z = 0 \; L > 5 \qquad (40)$$

$$T_{ave} = \frac{2}{3} T_{max} \qquad \text{for } Z = 0 \; L > 5 \qquad (41)$$

Equation (40) gives the maximum surface temperature, which occurs near $X = \bar{L}$ while equation (41) gives the average

surface temperature under the heat source.

The analysis which follows considers models (approximating the grinding process) to which the above analysis can be applied using varying heat source intensity.

3.2 Shear plane temperature :

The shear model of chip formation with a single cutting edge is shown in Fig.3.3. As an abrasive grain passes through the grinding zone, the undeformed chip thickness or grain depth of cut increases from zero to a maximum value. The temperature distribution along the shear plane can be estimated as follows .

The undeformed chip shape can be considered as a slender wedge if $t_{max} \ll \ell_c$. Therefore, undefomed chip thickness at any point

$$t_1 = \frac{\gamma}{\ell_c} t_{max} \qquad (42)$$

where γ is the distance from the beginning of the chip as shown in Fig.3.3.

Assuming shear angle ($\emptyset$) to be constant

$$\frac{t_2}{t_1} = \frac{1}{\sin\emptyset} = \text{constant} \qquad (43)$$

where t_2 is the heat source width as shown in Fig.3.3. Using equation (42) and (43), we get

$$t_2 = \frac{\gamma}{\ell_c} \frac{t_{max}}{\sin\phi} \tag{44}$$

The dimensionless half width will be given by

$$L = \frac{\gamma}{\ell_c} \cdot \frac{t}{\sin\phi} \cdot \frac{V}{2k} \tag{45}$$

The average shear plane heat flux $q_{s/p}$ is given by

$$q_{s/p} = K' \cdot \frac{F_c V}{btJ} \tag{46}$$

where K' is the fraction of cutting energy entering the work piece (≈ 0.6).

Using equations (17),(34),(40),(41),(45) and (46) we get the maximum and average shear plane temperature as

$$T_{max\ s/p} = K_s \sqrt{\frac{\gamma}{\ell_c}} \tag{47}$$

and $T_{ave\ s/p} = \frac{2}{3} T_{max\ s/p}$ (48)

where $K_s = 1.275 \frac{U_o c}{KJ} \left(\frac{kVdDr_o}{\sin\phi}\right)^{\frac{1}{2}}$ (49)

3.3 Sliding - Temperature :

The local temperature due to sliding between the wear land and the work - piece surface can be obtained using wear land as the heat source. Thus, we get the heat source strength as :

$$q_s = \frac{F_R V}{AJ} \tag{50}$$

Using equations (18) and (30) we get

$$q_s = K'' (1-\varphi)^{-1/6} \tag{51}$$

where $$K'' = \frac{4}{3}\,\frac{\mu K_1 K_2 U_o}{J}\left(\frac{vV^2 r_o}{2c}\sqrt{\frac{d}{D}}\right)^{1/3}$$

(52)

The dimensionless half - width is given by

$$L = \frac{V\varepsilon}{4k} \tag{53}$$

Using equations (6) and (16) we get

$$L = \frac{Vr_o}{k}\left[\frac{(r_o - d).d.\varphi}{r_o(2\varphi(r_o-d) + d)}\right]^{\frac{1}{2}} \tag{54}$$

Thus the maximum temperature due to rubbing is

$$T_{max_R} = K_{Rt}\left[\frac{(r_o-d).d.\varphi(1-\varphi)^{-2/3}}{r_o(2\varphi(r_o-d)+d)}\right]^{1/4} \tag{55}$$

where

$$K_{Rt} = \frac{2.408\, K_1 K_2 \mu U_o k^{\frac{1}{2}} r_o^{5/6}}{KJ}\left(\frac{v}{c}\sqrt{\frac{Vd}{D}}\right)^{1/3}$$

(56)

Therefore, the maximum temperature at any instance due to sliding can be evaluated.

3.4 Overall Interference - Zone Temperature :

To evaluate the temperature at the work surface, it will be assumed that no convective cooling occurs from the work piece surface and that a varying intensity moving heat source acts on the surface. Equations (40) and (41) can, therefore, be used. In terms of grinding variables, the dimensionless half width of the heat source is

$$L = \frac{\ell_c}{2} \quad \frac{v}{2k} = \frac{v\sqrt{dD}}{4k} (1-\varphi)^{\frac{1}{2}} \qquad (57)$$

The heat source strength is

$$q_I = K''' \frac{F_t \cdot V}{b \cdot \ell_c \cdot J} \qquad (58)$$

where K''' is the fraction of grinding energy entering the work piece. Sato (6) has shown that this is approximately 0.8.

Using equations, (37), (40), (41), (57) and (58) we get the maximum interference zone temperature (T_{max_I})

$$T_{max_I} = K_{It} \cdot \left[\frac{(1-\varphi)^{1/2} + K_t \left[\frac{2(r_o - d) \cdot d\varphi}{r_o(2\varphi(r_o - d) + d)} \right]}{(1-\varphi)^{5/12}} \right]$$

(59)

where

$$K_{It} = \frac{0.955\ U_o\ d^{5/12}\ D^{1/12}\ k^{1/2}}{KJv^{1/6}} (r_o c^2 V^2)^{1/3}$$

(60)

In the dimensionless form equation (59) can be written as

$$\frac{T_{max_I}}{K_{It}} = \left[\frac{(1-\varphi)^{1/2} + K_t \left[\frac{2(r_o - d)\, d\varphi}{r_o(2\varphi(r_o - d) + d)} \right]}{(1-\varphi)^{5/12}} \right] \qquad (61)$$

The average temperature on the finished work piece surface will be

$$T_{ave_I} = \frac{2}{3} T_{max_I} \qquad (62)$$

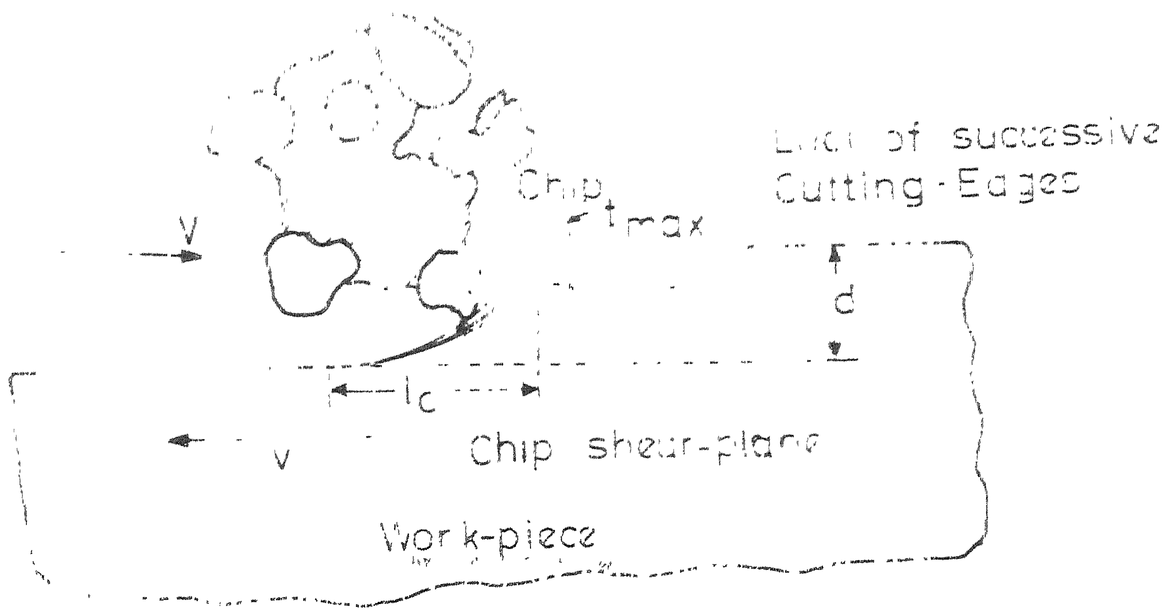


Fig. 3·1 CHIP FORMATION PROCESS.

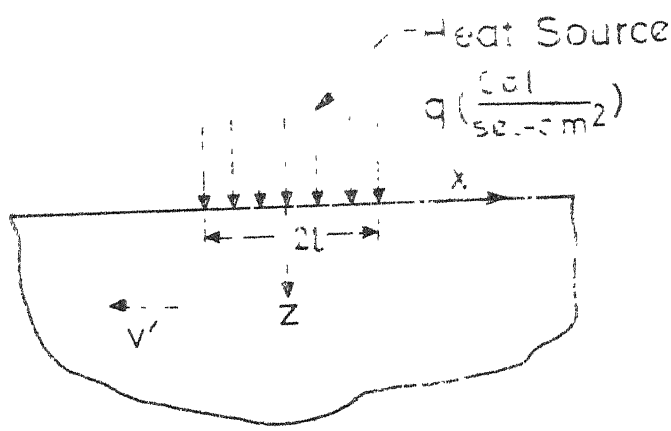


Fig. 3·2 BAND HEAT-SOURCE ON SEMI-INFINITE BODY.

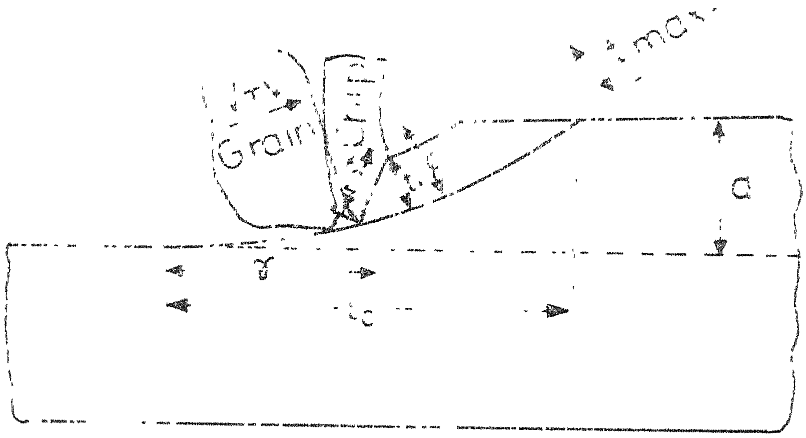


Fig. 3 3 CHIP SHEAR-PLANE GEOMETRY.

CHAPTER - IV

WHEEL - LIFE

4.1 Wear rate and Wheel-life :

Various experiments have been conducted and theories developed to measure or calculate the temperatures in grinding operation. A typical theoratical calculation is that of Des Ruisseaux and Zerkle (9), who suggested that the maximum temperature attained, when grinding mild-steel, may be as high as 902°C. Such high temperatures exist due to large scale plastic flow which occurs beneath the work-piece surface in front of and beneath the active grains. It is apparent therefore that the worn surface of a grain may be in intimate contact with a soft hot metal and that the worn flat of a grain may be subjected to an accelerated attritious wear mechanism which is associated with the welding and fracture of microasperities. Thus wear volume will be sensitive to increasing temperature values. Under conditions of extreme normal pressure or very high temperature, accelerated wear may occur during rubbing also, as noted by Vilenski and Shaw (18). In these circumstances, the wear rate ($\dot{\varphi}$) can be estimated from (11)

$$\dot{\varphi} = A_1 e^{-B/T} \max_R \qquad (63)$$

where T_{max_R} is the rubbing temperature and A_1 and B are the constants which can be evaluated experimentally for a given grinding condition. Equation (63) can also be written as

$$\int e^{B/T_{max_R}} d\varphi = A_1 \int dt + C_1 \qquad (64)$$

Substituting the value of T_{max_R} from equation (55) in the above equation and integrating, we get

$$t_g = \frac{e^{BT_o}}{A_1 BT_o'} \left[1 - e^{-BT_o'\varphi} \right] \qquad (65)$$

where t_g is the grinding time in minutes,

$$T_o = \left(\frac{1}{T_{max_R}}\right)_{\varphi = \varphi_o}$$

and $$T_o' = \frac{dT_o}{d\varphi}$$

and φ_o is the wear parameter at which the inflection point for force occurs (Table 5.2). This inflection point on the force time curve is the point which governs the wheel life or the time after which the redressing of the wheel is required.

Equation (65) gives the relation between wear and grinding time while the wheel life, τ, can be evaluated from

$$\tau = \frac{e^{BT_o}}{A_1 BT_o'} \left(1 - e^{-BT_o'\varphi_o} \right) \qquad (66)$$

Comparison with experimental results indicate that the error introduced by neglecting the term $e^{-BT'_o}\varphi_o$ in equation (66) is less than 5 o/o. Hence,

$$\tau \approx \frac{e^{BT_o}}{A_1 . BT'_o} \qquad (7)$$

Combining equations (63) and (67), we get

$$\dot{\varphi}\,\tau = \frac{1}{BT'_o} = \text{constant} \qquad (68)$$

CHAPTER - V

RESULTS AND DISCUSSION

5.1 Numerical Results :

Wheel Wear and Force Pattern :- Numerical calculations have been carried out for grinding conditions specified in Table 5.1. These are representative data for grinding steels. With the assumption that the individual grain on the grinding wheel is spherical in shape and as the grinding proceeds, the newly formed worn surface is paraboloid in shape, the wear land can be calculated using equation(18) for a given value of depth of cut, grain diameter and a dimensionless parameter φ. The wear land area is plotted in Fig. 5.1. From the numerical results presented, it is seen that as the wearing starts, the wear land area sharply increases in the beginning of the process and after that the growth is slow and steady. The grinding ratio (GR) can be obtained for specific grinding conditions using equation (27) if the depth of cut, grain diameter and the wheel diameter are known.

The rubbing force (F_R) can be estimated using equation (32) if the values of r_o, U_o, d, D, v, V, c, μ, K_1 and K_2 are known. The dimensionless rubbing force variation

is shown in Fig. 5.2. The curve shows that as the wearing proceeds, the rubbing force increases sharply (phase I) and then increases at a nearly constant rate for a long period (phase II). In the third phase, the force again increases rapidly. The variation of cutting force can be calculated using equation (34) if the grain size, depth of cut, wheel diameter, table speed, wheel speed, number of cutting edges per unit area and the specific energy for the process are known. The dimensionless cutting force is plotted against the dimensionless wearing parameter φ in Fig. 5.3. The curve shows that as the wearing proceeds with the process for a given value of depth of cut, the cutting force gradually decreases and when the wearing is equal to the depth of cut, the cutting force is zero. The total tangential grinding force can be calculated using equations (37) and (38), provided all the grinding parameters are known. The tangential force, F_t as a function of φ is shown in Figures (5.4) and (5,5). The curves show that the forces increase with increasing wear.

Grinding Temperatures : The shear plane temperature is determined from equations (47) and (49). The shear plane temperature as a function of position γ is shown in Fig. 5.6.

It is seen that the maximum shear plane temperature increases monotonically with increasing value of γ/ℓ_c. The calculated shear plane temperature approaches a value of $2120^{o}C$ as γ/ℓ_c approaches 1.0. The sliding temperature is determined from equations (55) and (56). This temperature as a function of φ is shown in Fig. 5.7 which shows that sliding temperature pattern is very similar to that of rubbing force pattern (Fig.5.3).

The overall interference zone temperature, which is the temperature of the finished work piece surface, can be evaluated using equations (59) and (60). The grinding parameters like D, r_o, v, V, d, U_o, k and K must be known. The maximum over all interference zone temperature is plotted against φ in Fig.(5.8) and (5.9). The curves show that the work piece temperature increases with increasing wear.

Wear rate and Wheel-life : The wear rate for given specific grinding conditions can be calculated using equation (63). The value of constant A_1 is 6.864 and B is 400/3 as obtained by feeding experimental datas in equation (67). The wheel-life can then be calculated using equation (67). Wheel-life for various values of depths of cut and table speeds are shown in Fig. 5.10.

5.2 Discussion :-

The variation of wear flat area shows that the wheel initially wears rapidly and after a certain time the wearing grows steadily. Since no experimental data is available for wear land area, it is not possible to give quantitative correlation between the experimental and theoratical values.

Grinding ratio is defined as the volume ratio of metal removed to wheel wear. Here an attempt has been made to give instantaneous values of grinding ratio which is likely to more accurate and realistic. A typical value of GR calculated using equation (27) for 46-J wheel at 10μ depth of cut was 32.9. This value has been evaluated for $\varphi = 0.3$. With 46 - J wheel the range of φ during phase II as evaluated was from 0.05 to 0.55 giving an average of 0.3. This value of GR is in excellent agreement with the experimentally measured value of 32 for 46 - J wheel and high carbon steel work piece.

The cutting force is maximum at the beginning and then decreases gradually (Fig.5.3). The rubbing force is, however, zero at the beginning (nominally sharp grain) and as the grinding proceeds this force increases. Experimentally it is not possible to measure the cutting

and rubbing forces independently and simultaneously but it is seen that the overall effect is such that the force increases as grinding is continued. This qualitative agreement is there between experiment and the theory. It can be seen from the theoratical curves, Fig.(5.4) and (5.5), that the forces increase with the increasing depth of cut and table speed. The major factors that govern the grinding forces are individual machine settings and their combinations in various forms, wheel dressing techniques, coolant selection and its application, wheel work piece material composition, rigidity of machine and so on. In the present analysis only attritious wear has been considered while in actual practice, there will always be bond as well as grain fracture. The tangential force values for various grinding conditions are given in Table 5.2.

Fig. 5.6 shows the shear plane temperature for a typical grinding condition. The maximum shear plane temperature is not much effected by wearing and is almost constant for a given set of grinding conditions. The temperature calculated along the chip increases with γ/ℓ_c and can reach a value much higher than the temperature on the work piece surface.Des Ruisseaux and Zerkle (9) have suggested that this is because the layer of material which

is being removed can act as a thermal insulator between the shear plane heat source and material which is not being removed. Since the grains on a grinding wheel are unevenly spaced and some remove larger volume of material than others, it is expected that variations in temperature will occur from one chip shear plane to another. Furthermore, the shear plane and chip geometries, and the shear plane heat flux can only be estimated with limited accuracy.

The sliding energy enters the work piece at the wear flat as shown in Fig.1.5 and this heat source moves along the work piece at the table speed. So the sliding energy is the main parameter which can be used for measuring wheel wear. Equations (55) and (56) show that the sliding temperature increases with increasing table speed, depth of cut and wheel speed. As the sliding temperature increases, the overall interference zone temperature also increases, since the total grinding energy conducted to the work piece increases with the increasing sliding energy. Thus the work piece temperature increases and it can reach such a high value that the austenite formation in the work piece surface can occur. At these temperatures, work piece burn will be visible. The effect of table speed and depth of cut upon the temperature distribution and work piece burn are clearly shown in Fig. (5.8) and (5.9). It is

seen that the work surface temperature is decreased as the table speed is increased while increasing depth of cut increases the work piece temperature. Thus the work piece burn can be avoided by using higher table speeds and lower depths of cut.

The wheel work interface temperature can similarly be decreased by decreasing the wheel depth of cut. The decrease in the table speed as well as grinding speed will also lead to lower temperatures. However, when the temperature rise in the work piece as a whole is to be considered, the higher table speed is preferrable for equilizing and decreasing the heat given to the work surface. Experimental results of Sato (6) clearly indicate this to be the case in actual practice. The total temperature on the work piece surface for different depths of cut and table speeds are given in Table 5.3.

The wheel life for any given grinding conditions can be evaluated using equation (67). The wheel-life is plotted against depth of cut for various table speeds in Fig. 5.10. Result shows that as the depth cut or table speed is increased the wheel life decreases. This is obvious because the increase in table speed or depth of cut increases the sliding temperature, thus increasing

the wear rate. Lower table speeds and depths of cut should, therefore, be used for increasing wheel-life. It has been shown earlier that lower table speeds are not preferable from the point of view of work piece burn, and dimensional accuracy. Thus it appears that there will be an optimum value of table speed for a given depth of cut which will give maximum wheel-life without causing work piece burn. These optimum values for various grinding conditions have been evaluated using equations (55) and (59). for the given datas in Table 5.1 (20).

Figure 5.11 gives a plot between wheel-life, depth of cut and table speed for optimum conditions. In the region above the v_{max} vs d curve, the wheel-life will decrease for a given depth of cut though burning spots will not appear, while in the region below this curve, the wheel-life will increase but work piece burn will occur. Since both these conditions are to be avoided, Fig. 5.13 can be used for obtaining optimum values for depths of cut and table speeds.

Equation (68) shows that the product of wheel-life and wear rate is a constant. Thus if the wheel life is known, wear rate can be calculated, provided the proportionality constant which is dependent upon the grinding

parameters, is known. This equation also shows that for higher wheel-life, wear rate must be decreased. Equation (63) clearly indicates that this is only possible by decreasing the sliding temperature which in turn can be decreased by decreasing the table speed, depth of cut or wheel speed.

TABLE 5.1 (20),(21)

Typical values of Grinding-parameters :-

Wheel : A-46-J-v-10, Work-piece : Med. C. Steel

Wheel speed	V	1355 m/min.
Wheel diameter	D	30 cm.
Table speed	v	15 m/min.
Depth of cut	d	.001-.0024 cm.
Wheel width		6.3 cm.
Cutting edges/cm^2	c	150
Initial grain radius	r_o	.016 cm.
Work-piece dimensions		5x1.2x2.5 cm.
Initial total horizontal grinding force	F_H	6Kg.
Shear-angle	ϕ	6^o, $\sin\phi \simeq 0.1$ (Assumed)
Thermal conductivity of work-piece material	K	0.124 Cal/cm.sec.^oC
Thermal diffusivity	k	0.138 cm^2/sec.
Specific energy of grinding	U	4.5×10^{11} dyne/cm^2
Average chip thickness	t	1.4×10^{-4} cm.
Constant	U_o	6.35×10^7 dyne/cm.
Coefficient of friction	μ	0.3
Fraction of cutting energy entering the work-piece	K'	0.6
Fraction of grinding energy entering the work-piece	K'''	0.8

Table 5.2(a)

Depth of cut-10μ, Grain diameter-.032cm., Table speed-15m/min.

Grinding Ratio, Tangential Force And Interference Zone temperature

Dimensionless wear parameter (φ)	Grinding Ratio GR	Tangential Force, F_t (Kg)	Interference Zone Temperature, (^oC)
.05	42.08	6.75	385.8
.15	36.87	7.668	450.81
.25	34.18	7.896	478.95
.35	31.65	7.974	501.30
.45	29.05	7.998	514.27
.55	26.25	8.001	551.48
.65	23.13	8.007	587.45
.75	19.54	8.031	641.15
.85	15.13	8.145	738.78

Table 5.2(b)

Grain diameter-.032cm, Table speed - 15m/min.

Constants K_t, K_1 and Tangential force at inflection point

Depth of cut, d (μ)	Dimensionless wear parameter at inflection point of force(φ_c)	K_t	K_1	Tangential force at inflection point (Kg)
10	.5557	17.782	8127.92	8.00
12	.5752	14.403	7900.27	8.85
16	.6058	10.323	7549.62	9.85
20	.6296	7.974	7289.95	10.83
24	.6488	6.463	7090.18	12.10

Table 5.3

Interference Zone Temperature and Wheel Life

Grain diameter-0.032cm.,Table speed- 25cm/sec.

Depth of cut $d(\mu)$	Interference Zone Temperature at φ_0 ($^\circ$C)	Wheel life, τ (min.)	
		Experimental	Theoretical
8	520.2	1.359	1.277
10	557.6	0.720	0.761
12	594.6	0.440	0.544
16	655.8	-	0.381
20	712.5	-	0.318
24	757.5	-	0.290

Grain diameter-0.032 cm., Depth of cut- 10μ.

Table Speed v(cm./sec.)	Interference Zone Temperature at φ_0 ($^\circ$C)
5	732.0
10	652.5
15	610.1
20	572.3
25	547.5
30	523.8

CHAPTER-VI

CONCLUSION

The following conclusions can be derived from the theoratical analysis developed for evaluating wear, grinding forces and grinding temperatures :

The wear flat area grows rapidly at the beginning of the process and then the wear growth is relatively low. The GR is not much effected by changing the depth of cut or table speed. The cutting forces increase with increase in depth of cut, table speed and wheel diameter but decrease with increase in wheel speed. For a given grinding conditions the cutting force decreases as the process advances, while the rubbing force increases. Similarly rubbing force increases with increase in v and d but decreases when V and D are increased. The total tangential force increases with increasing table speed and depth of cut and decreasing wheel velocity.

The shear plane temperature is not much effected by wheel wear but increases proportionally to $V^{0.5}$, $d^{0.5}$ and $D^{0.5}$. The sliding temperature and wheel life can be considered simultaneously. The sliding temperature on the other hand, increases with wear and increases proportionally to $v^{.33}$, $V^{.166}$ and $d^{.166}$ while decreases proportionally to $D^{-.166}$. The increasing sliding temperature decreases the

wheel life. Accordingly in order to increase the wheel life, it is important to use smaller depths of cut and lower table speeds.

The overall interference zone temperature increases with increase in d or V and decreases when v is increased. Since overall interference zone temperature is the temperature on the finished work piece surface, work piece burn can be avodded by increasing table speed.

The effect of the table speed on the grinding temperature is such that its increase causes the wheel life to decrease and when it is decreased the work piece burn occur. It is therefore, important to choose some optimum value of table speed for a given depth of cut to obtain maximum wheel life without burn.

Comparison with available experimental results gives qualitative agreement with the analytical results.

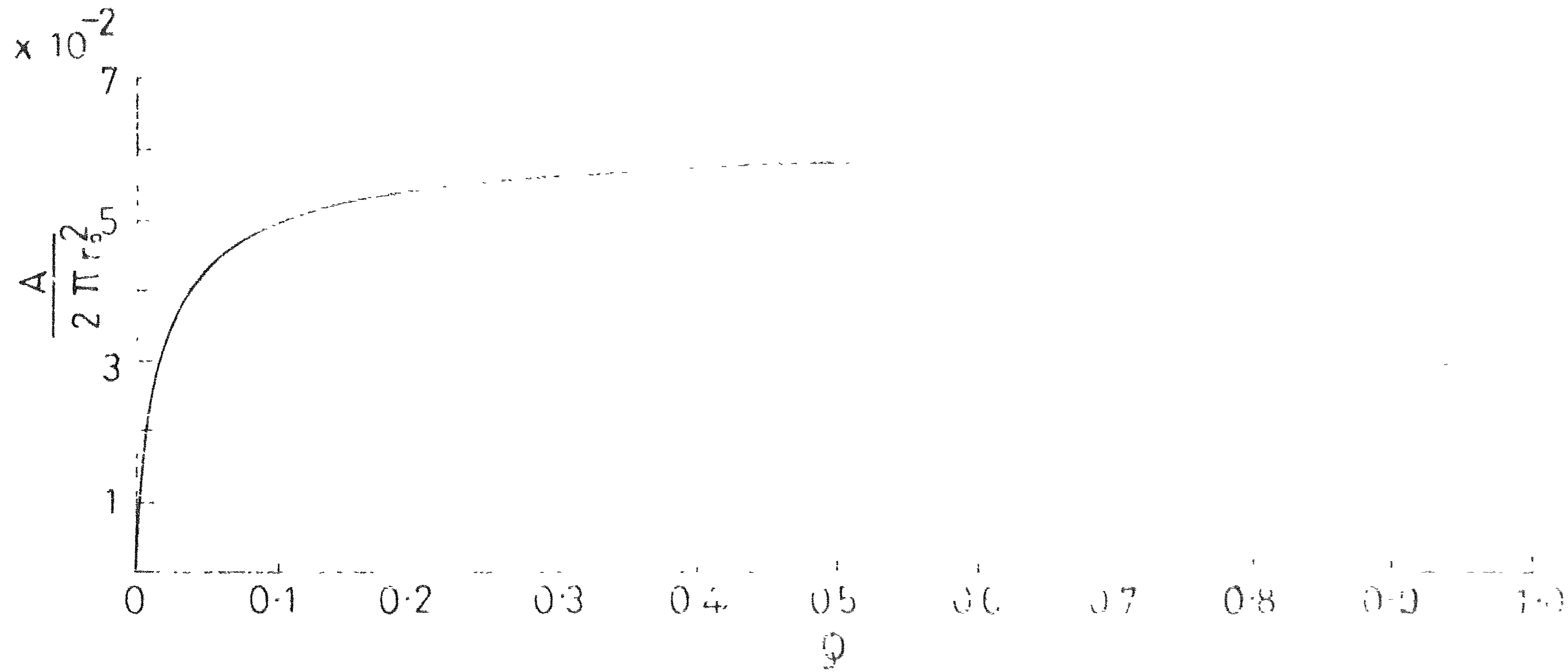


Fig. 5·1 VARIATION OF WEAR FLAT AREA (A) WITH DIMENSIONLESS WEAR PARAMETER (φ).

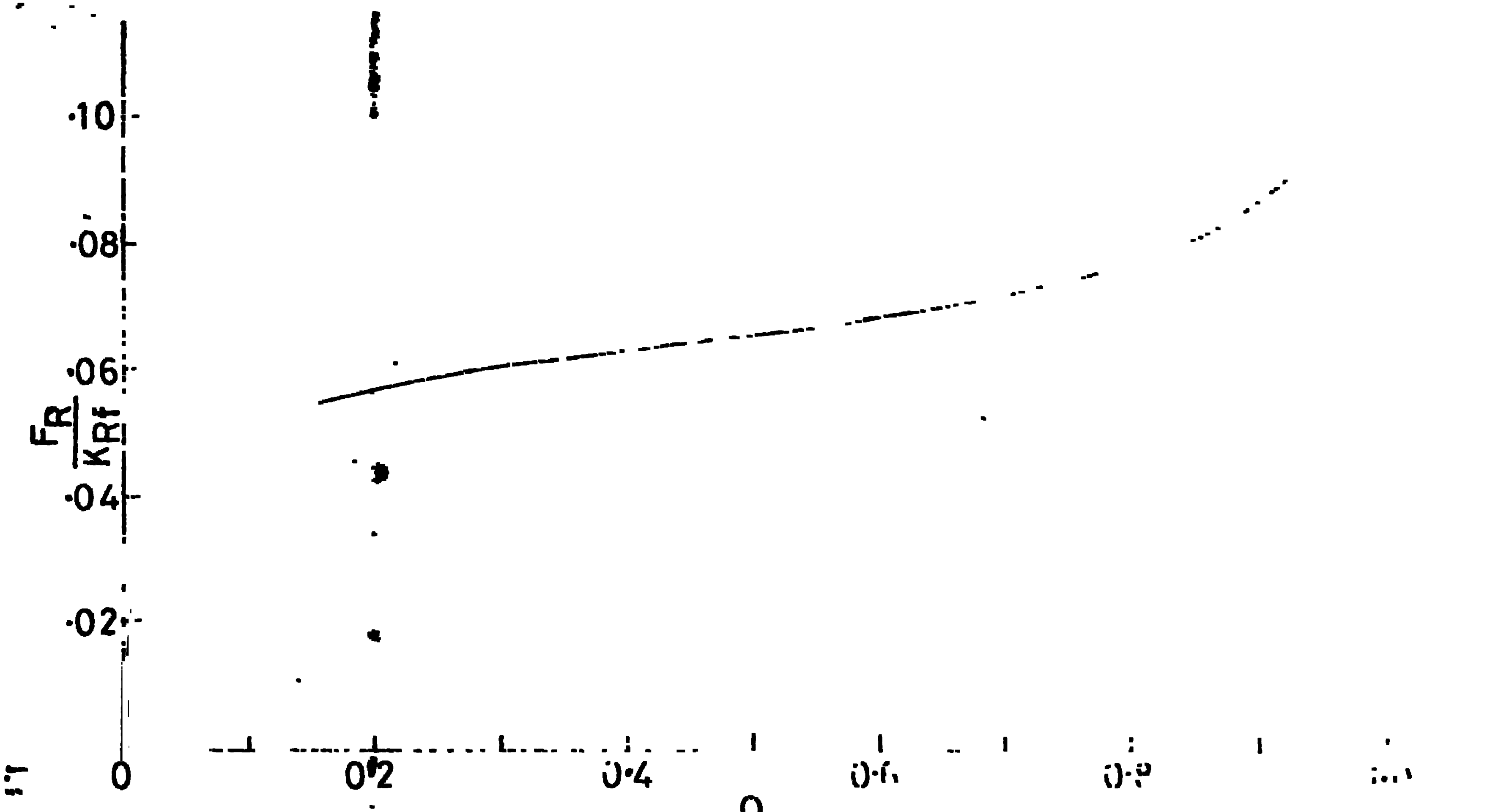


Fig. 5·2 VARIATION OF RUBBING FORCE (F_R) WITH DIMENSIONLESS W... PARAMETER (Q).

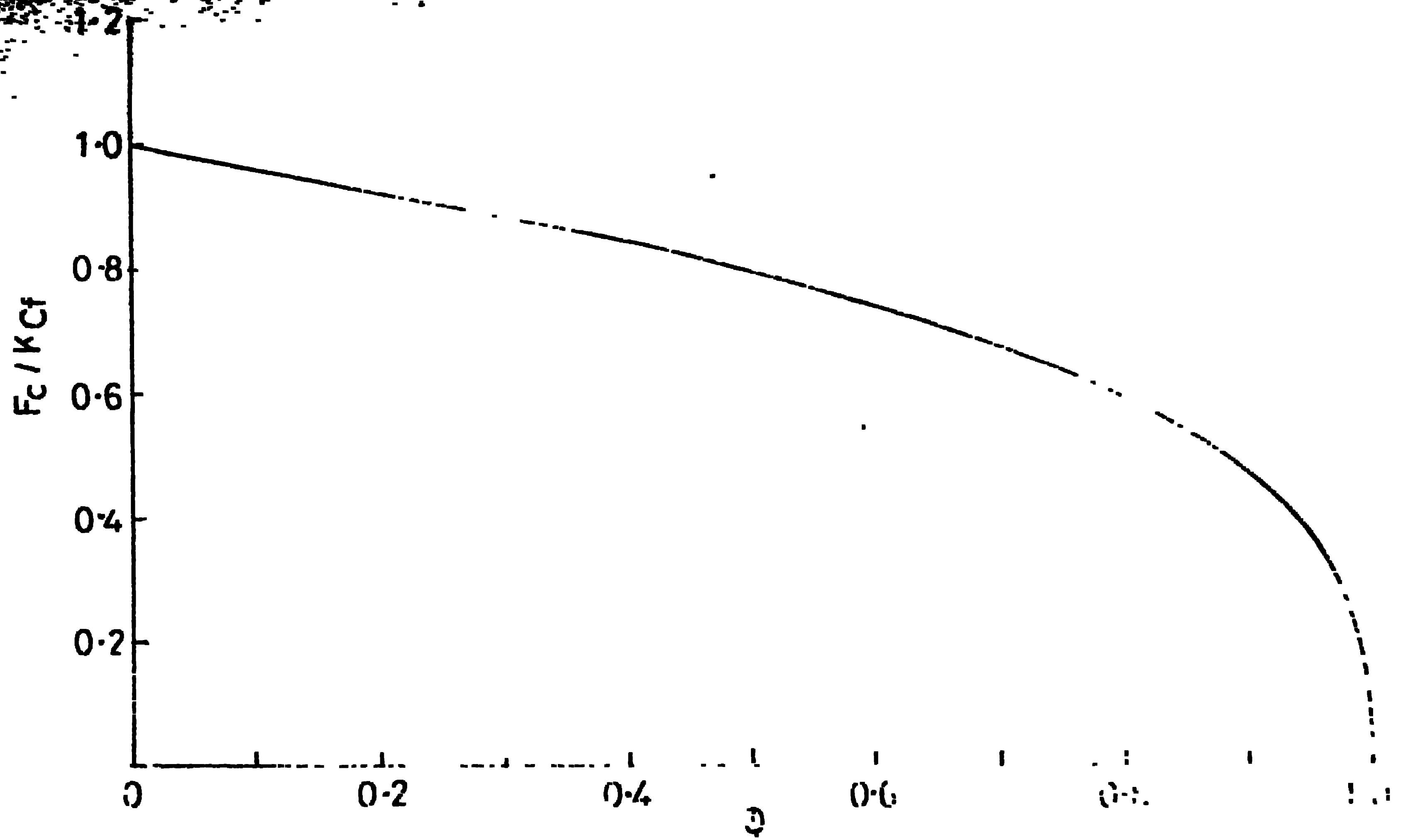


Fig. 5·3 VARIATION [illegible] (F_c) WITH [illegible]
PARAMETER (φ).

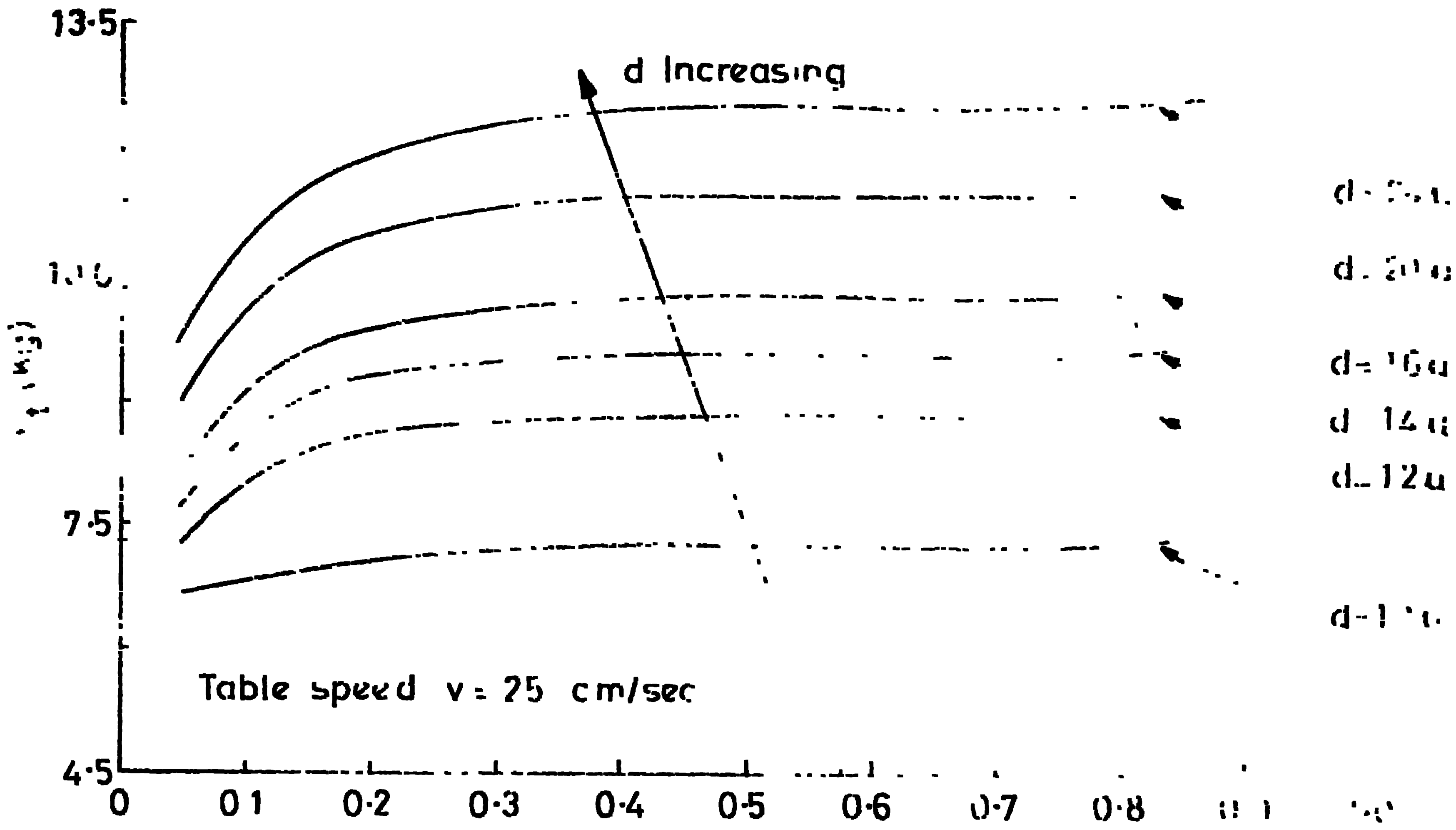


Fig. 5·4 VARIATION OF TANGENTIAL FORCE (F_t) WITH (Q) FOR DIFFERENT DEPTH OF CUT (d).

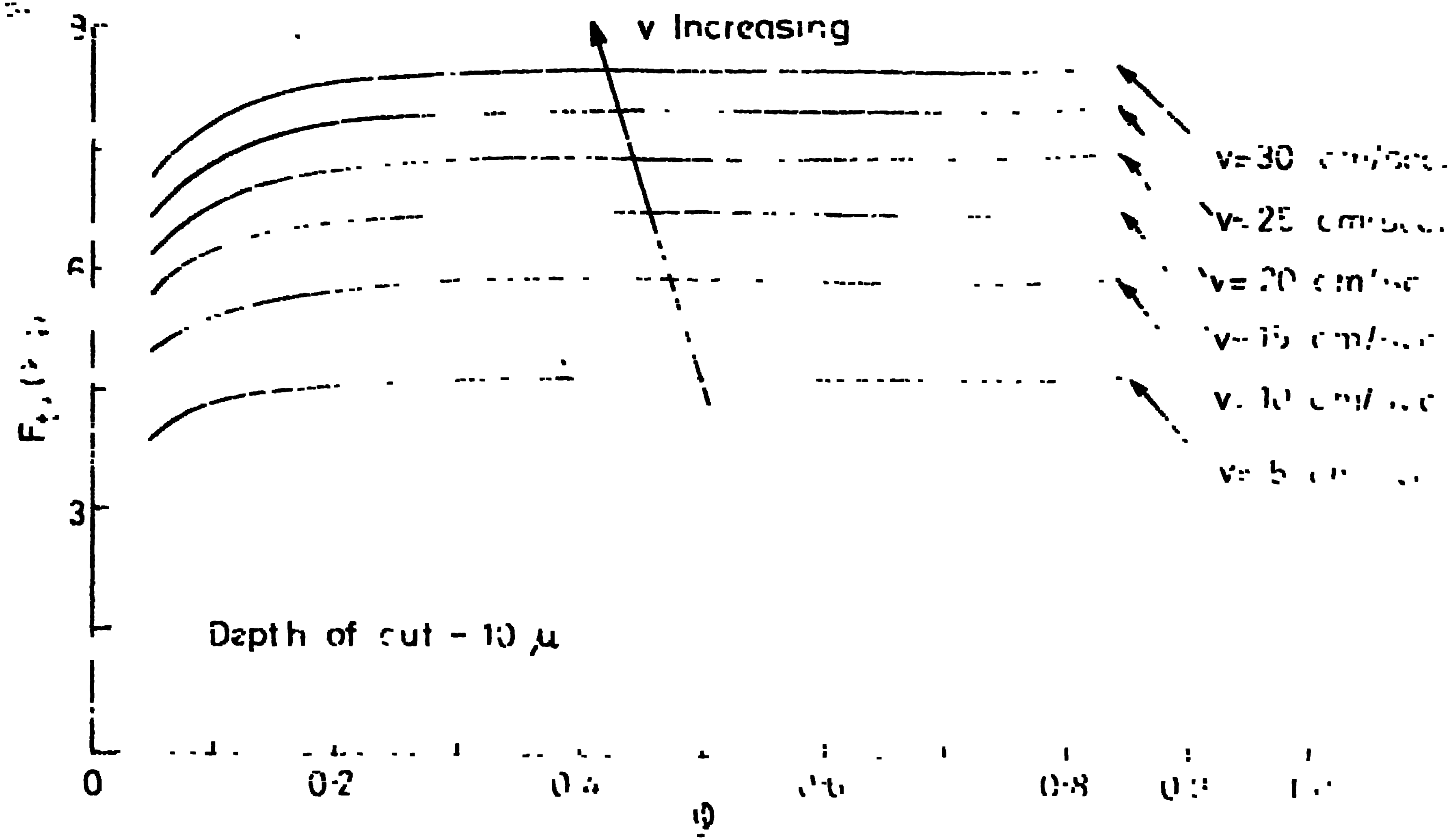


Fig. 5·5 VARIATION OF TANGENTIAL FORCE (F_t) WITH [illegible] PARAMETER (ϕ) FOR VARYING TABLE [illegible]

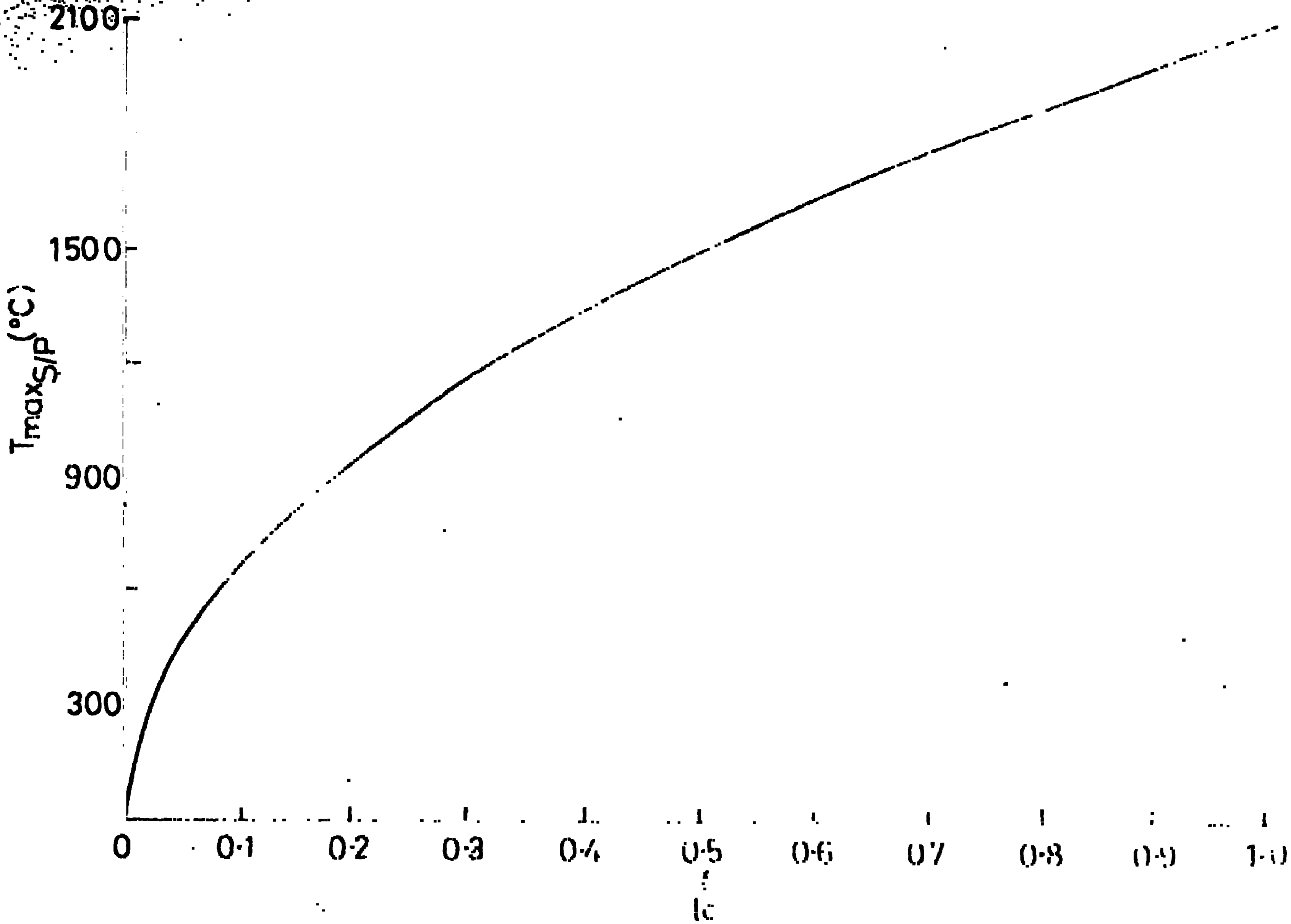


Fig 5·6 VARIATION OF MAXIMUM [illegible] ([illegible]
WITH ([illegible]) ALONG THE [illegible]

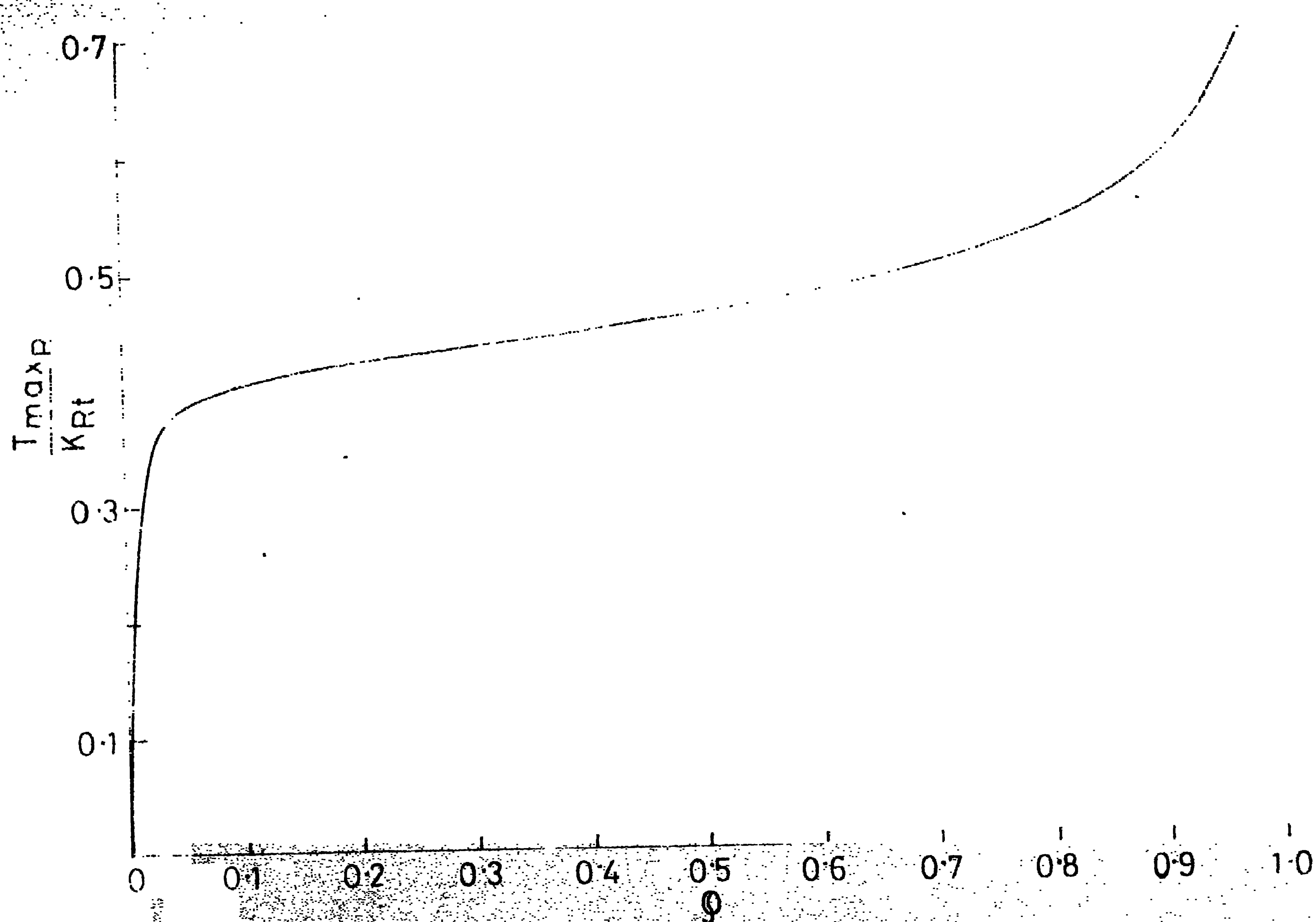


Fig. 5·7 VARIATION OF MAXIMUM SLIDING TEMPERATURE (T_{max_R}) WITH DIMENSIONLESS WEAR PARAMETER ($\wp$).

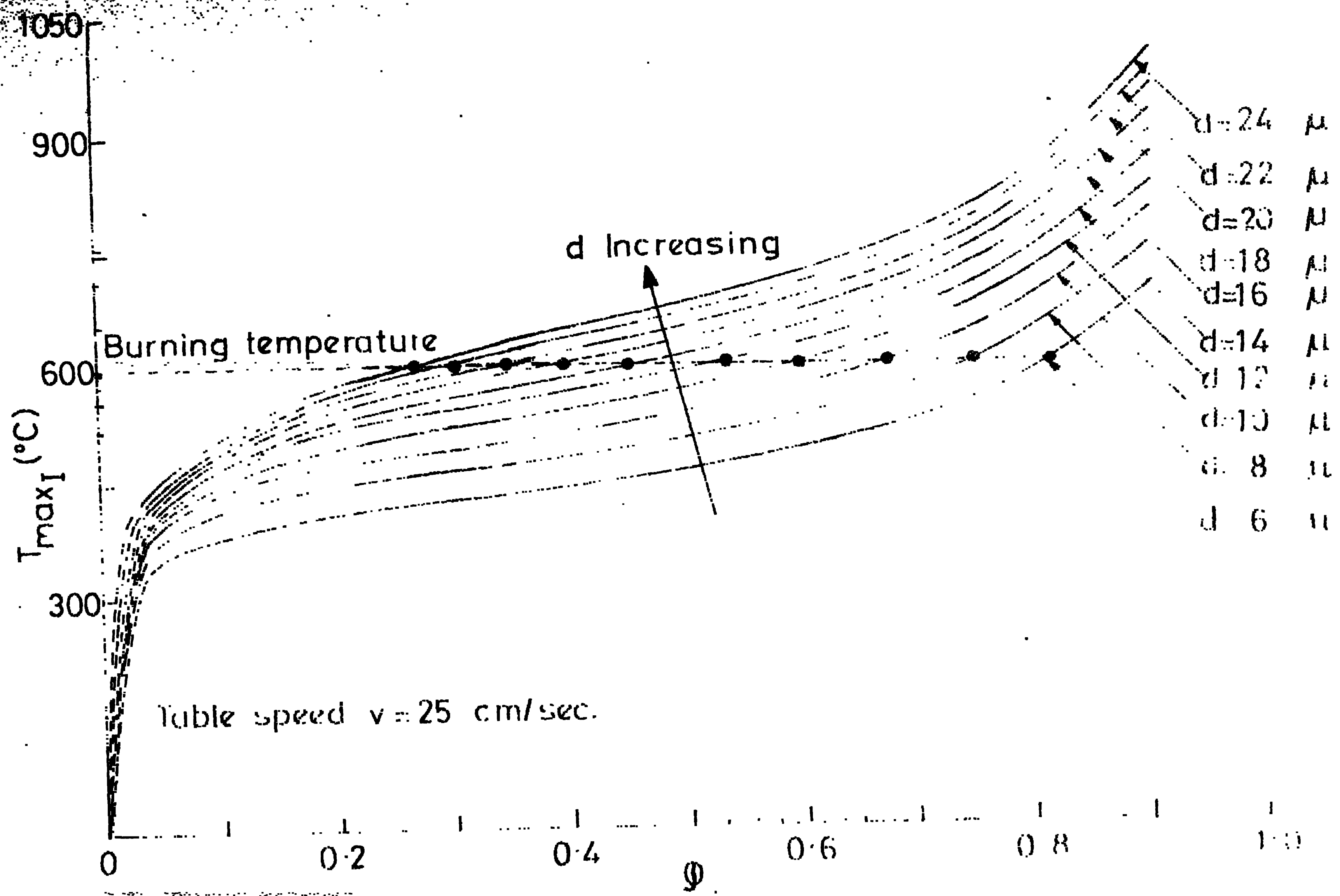


Fig. 5·8 VARIATION OF OVER ALL INTERFERENCE ZONE TEMPERATURE (T_{max_I}) WITH DIMENSIONLESS WEARPARAMETER ($\wp$) FOR VARYING DEPTH OF CUT (d).

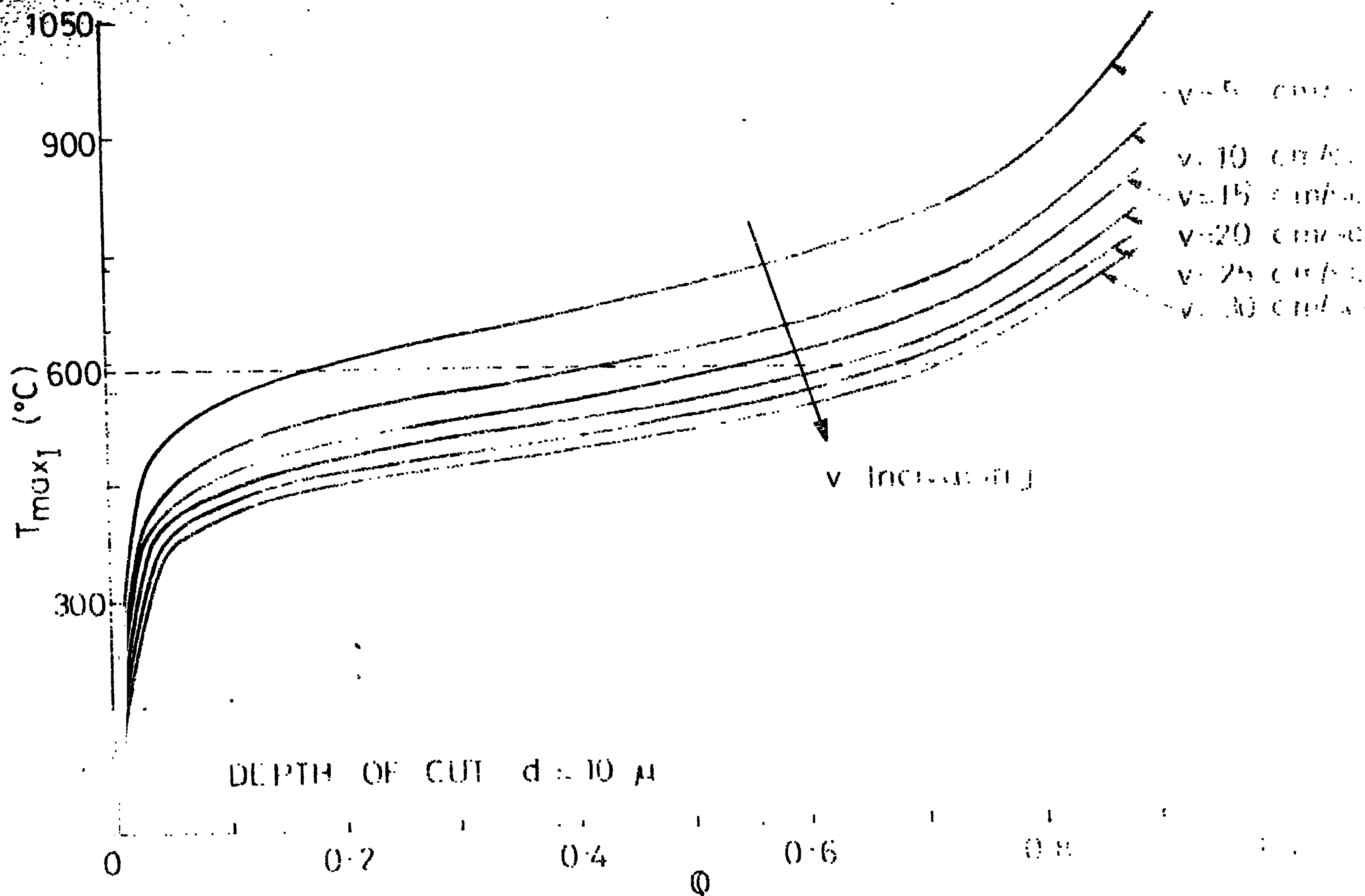


Fig. 5·9 VARIATION OF MAXIMUM OVER ALL INTERFERENCE ZONE TEMPERATURE (T_{max_I}) WITH DIMENSIONLESS WEAR PARAMETER (φ) FOR DIFFERENT TABLE SPEED (v).

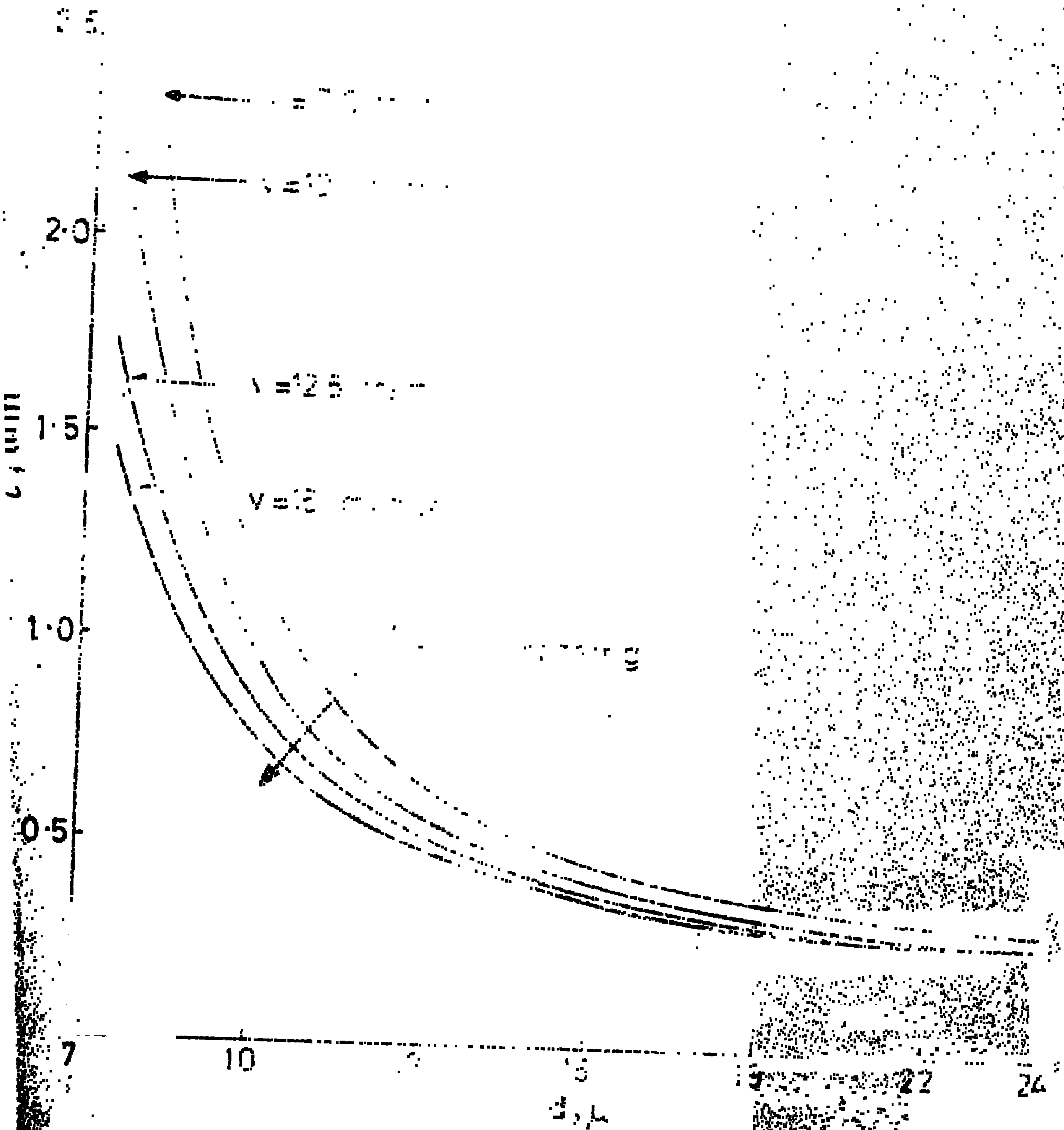
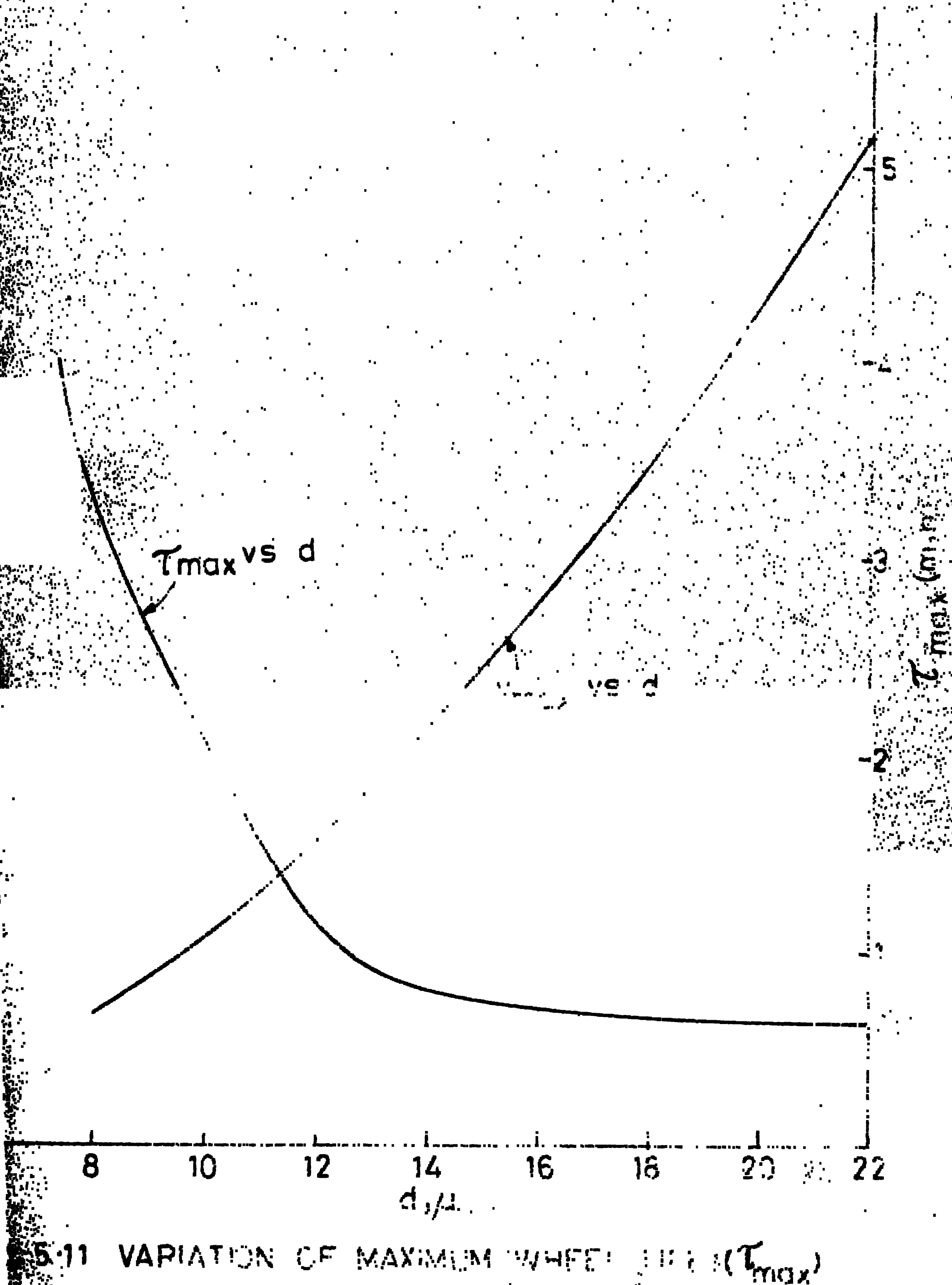


Fig. 5·10 VARIATION OF WHEEL-D... WITH DEPTH OF CUT ...



5·11 VARIATION OF MAXIMUM WHEEL ... (τ_{max}) AND OPTIMUM ... OF TABLE SPEED (...) WITH DEPTH OF CUT (d).

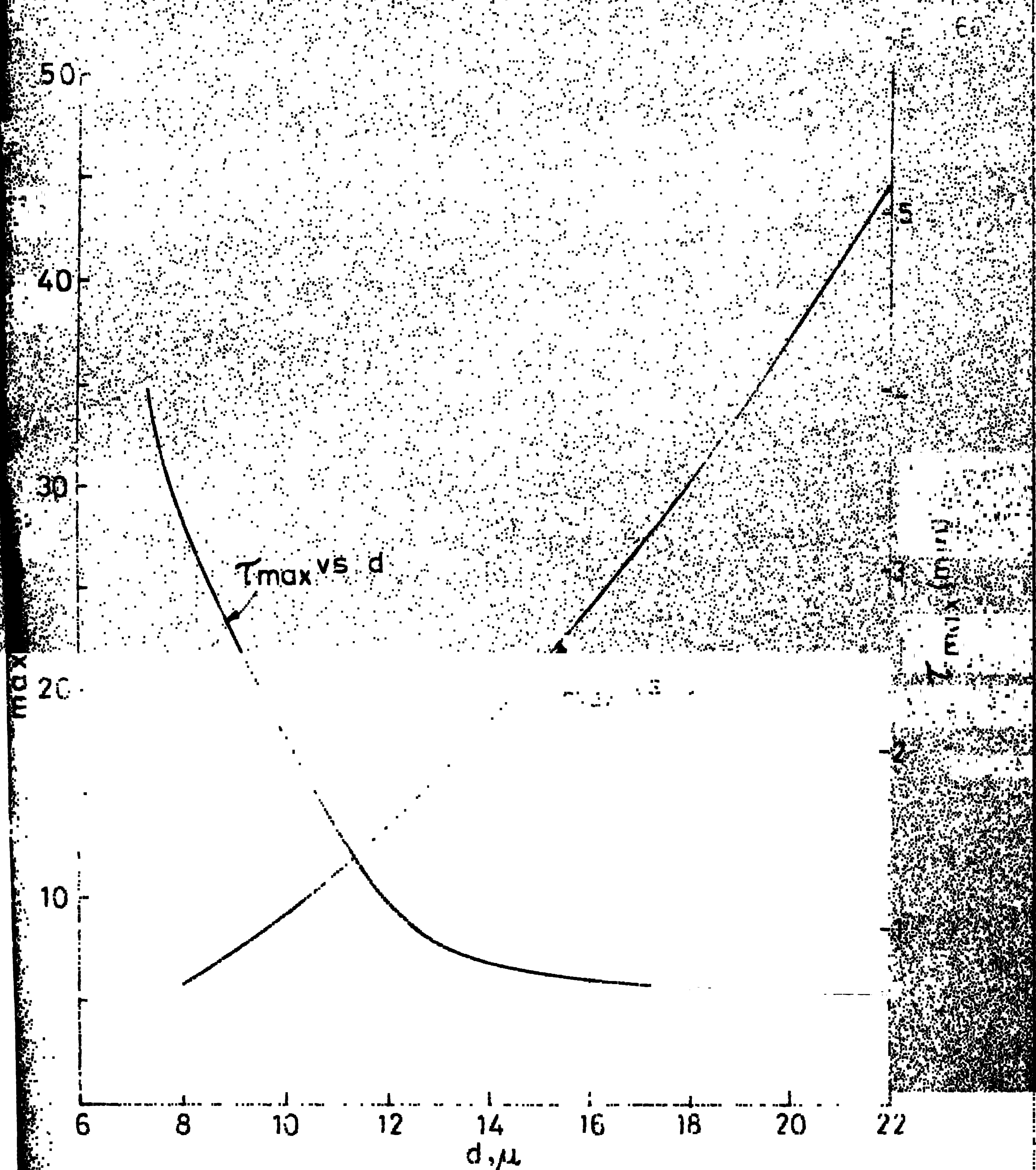


Fig. 5·11 VARIATION OF MAXIMUM WHEEL LIFE (τ_{max}) [illegible] OPTIMUM VALUE OF [illegible] [illegible] WITH DEPTH OF CUT [illegible]

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